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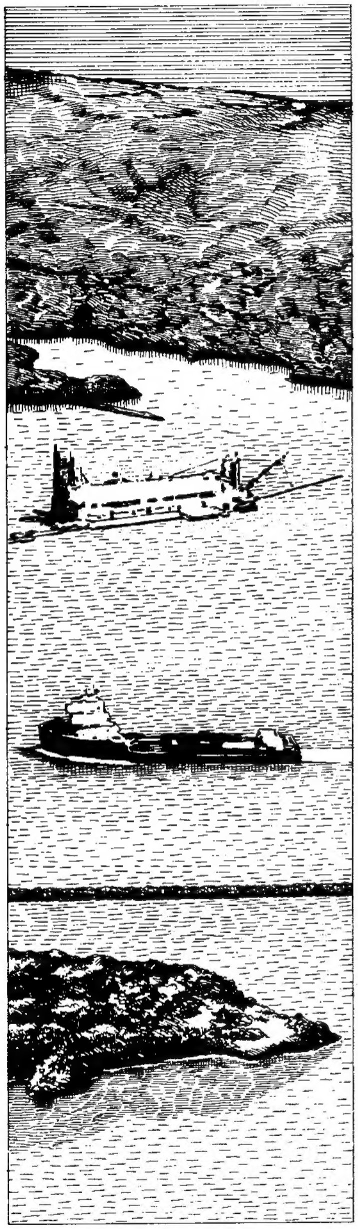

DREDGING RESEARCH PROGRAM

TECHNICAL REPORT DRP-95-5

DESCRIPTORS FOR BOTTOM SEDIMENTS TO BE DREDGED: SUMMARY REPORT FOR WORK UNIT NO. 32471

Compiled by

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July 1995

Final Report

Approved For Public Release; Distribution Is Unlimited

Prepared for DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-1000

Under Work Unit 32471

The Dredging Research Program (DRP) is a seven-year program of the U.S. Army Corps of Engineers. DRP research is managed in these five technical areas:

- Area 1 - Analysis of Dredged Material Placed in Open Water
- Area 2 - Material Properties Related to Navigation and Dredging
- Area 3 - Dredged Plant Equipment and Systems Processes
- Area 4 - Vessel Positioning, Survey Controls, and Dredge Monitoring Systems
- Area 5 - Management of Dredging Projects

Dredging Research Program Report Summary

US Army Corps of Engineers
Waterways Experiment Station

Descriptors for Bottom Sediments to be Dredged: Summary Report for Work Unit No. 32471 (TR DRP-95-5)

ISSUE: Standard dredging-related geotechnical descriptors are needed so that engineering properties can either be given directly or be readily inferred for engineering applications such as dredgeability.

RESEARCH: Descriptive terms were developed that are related to a classification system for indicating or readily inferring the dredgeability of in-situ sediments. Also a knowledge-based expert system (KBES) was developed to provide access to record expertise and guidance from experts in their respective fields for use by geotechnical engineers planning a subsurface investigation and by dredging estimators and contractors for interpreting the dredgeability of a proposed dredging project.

SUMMARY: Several Dredging Research Program (DRP) products were identified that were designed to reduce or eliminate adverse impacts of contractor claims of changed conditions arising from incomplete geotechnical information provided to potential dredging contractors. The proposed dredging classification system places all subbottom materials in one of eight groups, each with differing fundamental dredging characteristics. Each of the eight groups is considered from the standpoint of four different dredgeability properties. When any kind of material is considered by each of the four dredgeability evaluations, the dredgeability of the in-situ sediment can be directly indicated or readily inferred. The KBES GEODREDG consists of two modules:

(a) DREDGABL provides guidance in interpretation of geotechnical properties data for estimating the dredgeability of sediment;

(b) GEOSITE contains guidance in the selection of methods and equipment for sampling and testing sediments to obtain information necessary for determining dredgeability.

AVAILABILITY OF REPORT: The report is available through the Interlibrary Loan Service from the U.S. Army Engineer Waterways Experiment Station (WES) Library, telephone number (601) 634-2355. National Technical Information Service (NTIS) report numbers may be requested from WES librarians. To purchase a copy of the report, call NTIS at (703) 487-4780.

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Dredging Research Program

Technical Report DRP-95-5
July 1995

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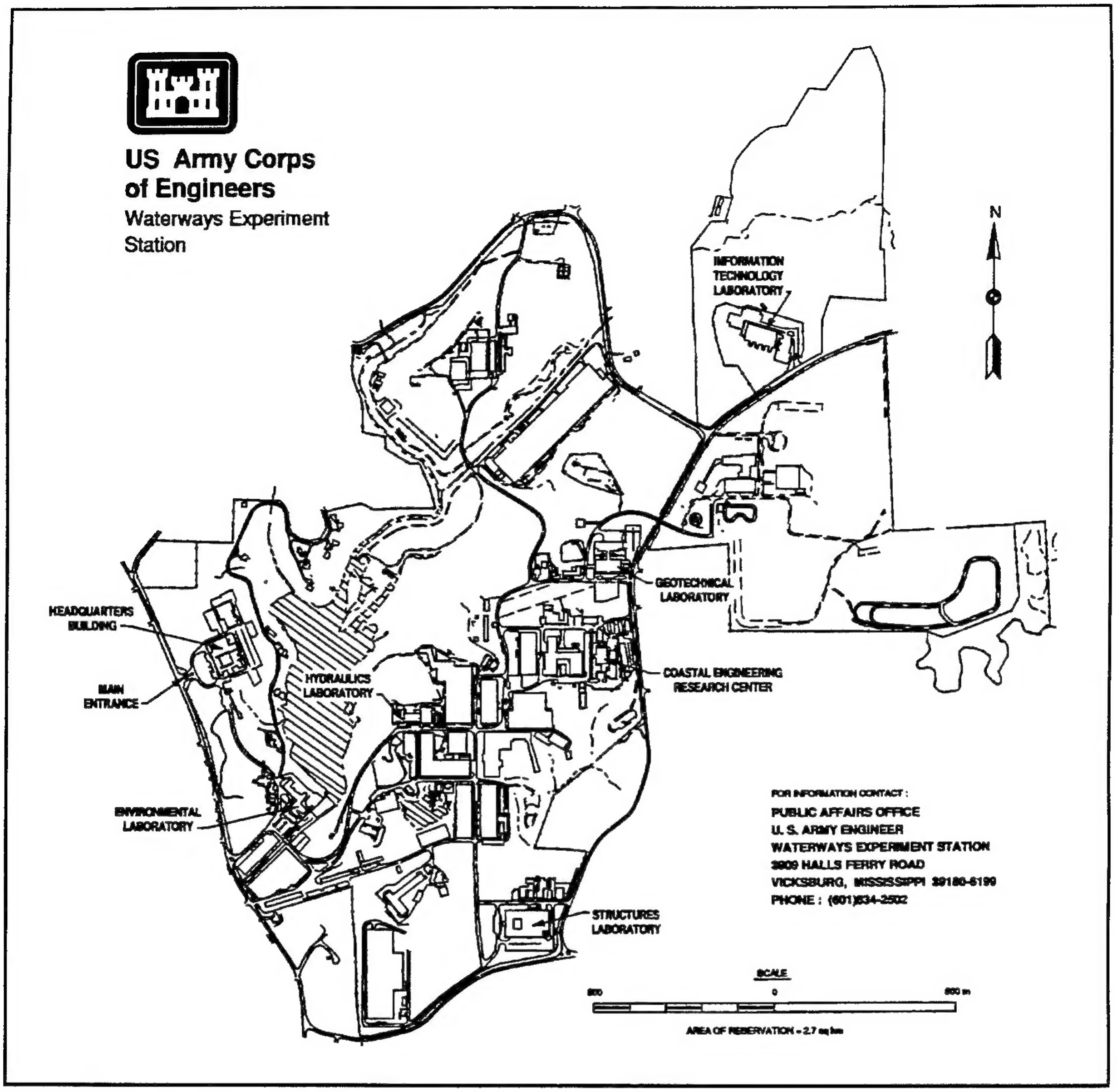

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Preface

This report summarizes research conducted under U.S. Army Engineer Waterways Experiment Station (WES) Dredging Research Program (DRP) Work Unit No. 32471, "Descriptors for Bottom Sediments to be Dredged," a part of Technical Area 2, "Material Properties Related to Navigation and Dredging." The DRP is sponsored by Headquarters, U.S. Army Corps of Engineers (HQUSACE). Technical Monitors for Technical Area 2 were Messrs. Barry W. Holliday and David A. Roellig (retired), HQUSACE.

This summary report was compiled by Dr. Lyndell Z. Hales, Coastal Engineering Research Center (CERC), WES, and was extracted essentially verbatim from contract reports written by Dr. S. Joseph Spigolon, SJS Corporation, Coos Bay, OR; Dr. Dov Leshchinsky, Professor of Civil Engineering, University of Delaware, Newark, DE, and Dov Leshchinsky Associates, Newark, DE; Dr. Stephen D. Richter, Dov Leshchinsky Associates, Newark, DE; and Dr. Reda M. Bakeer, Associate Professor of Civil and Environmental Engineering, Tulane University, New Orleans, LA.

The contract studies were conducted under the technical oversight of Dr. Jack Fowler (retired), Principal Investigator, Soil Mechanics Branch (SMB), Soil and Rock Mechanics Division (S&RMD), Geotechnical Laboratory (GL), WES. Additional supervision was provided by Mr. G. B. Mitchell (deceased), former Chief, SMB, and Mr. W. Milton Myers, present Chief, SMB; Dr. Don C. Banks, Chief, S&RMD; Dr. Paul F. Hadala (retired), Assistant Director, GL; and Dr. William F. Marcuson III, Director, GL. Dr. Banks and Mr. Hardy J. Smith, Rock Mechanics Branch, S&RMD, were the Technical Area Managers for Technical Area 2.

Mr. E. Clark McNair, Jr., CERC, and Dr. Hales were Manager and Assistant Manager, respectively, of the DRP. Dr. James R. Houston and Mr. Charles C. Calhoun, Jr., were Director and Assistant Director, respectively, of CERC, which oversees the DRP.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

For further information on this report or on the DRP, please contact Mr. E. Clark McNair, Jr., DRP Program Manager, WES, at (601) 634-2070.

Conversion Factors, Non-SI to SI (Metric) Units of Measurement

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
feet	0.3048	meters
feet per second	0.3048	meters per second
inches	2.54	centimeters
pounds (force)	4.448222	newtons
pounds (force) per square inch	6.894757	kilopascals
tons force per square foot	9773.6	kilograms per square meter

Summary

This report summarizes research conducted under U.S. Army Engineer Waterways Experiment Station (WES) Dredging Research Program (DRP) Work Unit No. 32471, "Descriptors for Bottom Sediments to be Dredged." Standard dredging-related geotechnical descriptors are critically needed so that engineering properties can be either given directly or can be readily inferred for engineering applications such as dredgeability prediction. Dredgeability is taken to mean the ability to excavate underwater, remove to the surface, transport, and deposit sediments with respect to known or assumed equipment, methods, and in-situ material characteristics.

Descriptive terms provide word equivalents to the numbers resulting from soil identification tests. When numerical definitions for the words are consistent, word descriptors are practical for communicating information. Consistent descriptive terms for sediments to be dredged have been proposed. These descriptive terms are related to a classification system for indicating or readily inferring the dredgeability of in-situ sediments.

The proposed dredging classification system places all materials in one of eight groups, each with different fundamental dredging characteristics. New work may encounter any of the eight groups. The eight groups are: (a) rock and coral, (b) shale and cemented soils, (c) boulders and cobbles, (d) clean granular soils, (e) friable mixed-grain soils, (f) cohesive soils, (g) highly organic soils, and (h) fluid mud. Each of these eight groups is considered from the standpoint of four different dredgeability property evaluations: (a) geotechnical properties, (b) excavation properties, (c) removal and transport properties, and (d) disposal properties. When the eight different kinds of materials are considered from four different dredgeability property evaluations, the dredgeability of the in-situ sediments can be directly indicated or readily inferred.

A knowledge-based expert system (GEODREDG) has been developed to provide access to recorded expertise and guidance from experts in their respective fields for use by geotechnical engineers planning a subsurface investigation and by dredging estimators for interpreting dredgeability of a proposed project. GEODREDG consists of two modules: (a) DREDGABL--guidance in the interpretation of geotechnical properties data for estimating the dredgeability of sediments, and (b) GEOSITE--guidance in the selection of methods and

equipment for sampling and field and laboratory strength testing of sediments to obtain information necessary for determining dredgeability.

The DRP also produced several new products under separate work units designed to reduce or eliminate adverse impacts of claims of changed conditions arising from incomplete geotechnical information provided to potential dredging contractors. These new technologies were developed to enhance the ability of the Corps of Engineers to obtain more precise and comprehensive geological data about proposed dredging projects, with particular reference to new work dredging. These new products include: (a) an acoustic impedance technique for subbottom imaging, (b) an inexpensive vibracoring sampling device, (c) a drilling parameter recorder, and (d) a point load test for saturated rock.

1 Introduction

This report summarizes research conducted by U.S. Army Engineer Waterways Experiment Station (WES) Dredging Research Program DRP Work Unit No. 32471, "Descriptors for Bottom Sediments to be Dredged," a part of Technical Area 2, "Material Properties Related to Navigation and Dredging." Justification for conducting this research was presented by Calhoun et al. (1986):

> ...The development of standard dredging-related descriptors for in-situ material is critically needed. The methods of observation and the descriptors now used represent a mixture adopted (sometimes not adapted) from diverse fields such as environmental engineering, geology, soil mechanics, and foundation engineering. Descriptors need to be developed such that engineering properties are either directly given or can be readily inferred for engineering applications such as dredgeability prediction. The term 'dredgeability' is taken to mean the ability to excavate underwater with respect to known or assumed equipment, methods, and in-situ material characteristics...

For purposes of the studies in the work unit, the above definition of 'dredgeability' was modified to encompass the effect of sediment properties on the entire dredging process; i.e.,

> ...The term 'dredgeability' is taken to mean the ability to excavate underwater, remove to the surface, transport, and deposit sediments with respect to known or assumed equipment, methods, and in-situ material characteristics...

This summary report considers only in-situ soil sediments to be dredged; rock characteristics were investigated in a separate work unit. Both maintenance and new work dredging of sediment in the marine environment and inland waterways were considered.

Chapter 2 of this report presents a geotechnical site-investigation strategy for dredging projects (Spigolon 1993b). Methods of underwater geotechnical site investigation directly applicable to dredging projects are described, and factors that must be considered in planning a site investigation are defined, so that a rational subbottom investigation strategy may be formulated.

Chapter 3 discusses geotechnical factors in the dredgeability of sediments and the resulting descriptors for sediments to be dredged (Spigolon 1993a). A procedure to develop unbiased descriptors for granular bottom sediments to be dredged was presented by Leshchinsky (1994). Richter and Leshchinsky (1994) quantified empirically the relationships between basic clay properties and the degradation rate of hydraulically transported clay balls.

Chapter 4 provides guidance in the geotechnical evaluation of the dredgeability of sediments using a knowledge-based expert system "GEOtechnical Factors in DREDGing (GEODREDG)" (Spigolon and Bakeer 1993) that contains two subsystems. The "Geotechnical Factors in DREDGeABiLity (DREDGABL)" program provides guidance in the interpretation of geotechnical descriptors of sediments in terms of their dredgeability properties (Spigolon and Bakeer 1994c). The "GEOtechnical SITE-Investigation Methods (GEOSITE)" program was developed for use by engineers and geologists in planning a subsurface investigation for a dredging project (Spigolon and Bakeer, in preparation).

Chapter 5 is a discussion of the geotechnical engineering and other bottom sediment descriptor knowledge gained from DRP research as applicable to reducing contract claims at dredging projects by minimizing the impact of differing site conditions (Spigolon, in preparation).

Chapter 6 is a synopsis of the technical reports pertaining to "Descriptors for Bottom Sediments to be Dredged" that were produced from research investigations conducted by the DRP during development of dredging-related descriptors for in-situ materials.

2 Geotechnical Site-Investigation Strategy for Dredging Projects[1]

The objective of a geotechnical site investigation for a dredging project is to obtain the most complete and accurate estimate of the location and character of the materials to be dredged that is possible within the limits of available time, money, and practicality. This information must then be communicated in a readily understood manner to all persons involved in the design, cost estimation, and construction of the project. A site investigation for dredging consists of studies of all available existing information augmented by geophysical and geotechnical subbottom investigations, including the sampling and testing of soils/sediments. Data are summarized in a predicted geotechnical subbottom profile. The validity of the predicted profile is dependent on the type and extent of site investigation made and on the knowledge and skill of the interpreter(s) of the data.

Bids submitted on a project are affected by the monetary risks the contractors are willing to take after considering their uncertainty about the character and location of the materials to be dredged. The greater the risk from incomplete information, the greater that part of the bid price that considers the risk. If unforeseen adverse site conditions are encountered, the contractor may file a claim for changed conditions. Therefore, the amount to be spent on a site investigation by the owner is directly related to the amount that the bid price and the total cost involved in processing claims for changed conditions can be reduced by the availability of a more comprehensive geotechnical site description.

[1] Chapter 2 was extracted from Spigolon (1993b).

Soil Properties Affecting Dredging Operations

Dredgeability properties of soil sediments

Soil sediments have different dredgeability properties during the three stages of a dredging project (excavation, removal and transport, and disposal stages). The dredgeability properties for each stage of the operation include:

a. Excavation.

Suctionability. Facility with which a sediment can be excavated by plain suction (the sediment is drawn into a hydraulic pipe at or very near its in-situ density, i.e., with little or no diluting water).

Erodibility (scourability). Ease with which a sediment can be excavated by shearing or direct impact of a fluid moving parallel or at an angle to the sediment surface.

Cuttability. Relative ease with which a sediment can be excavated by a blade, knife, or plow. Properties that govern cuttability include shear strength, grain-size distribution (percent fines), plasticity, and adhesion to a metal cutting surface.

Scoopability (digability). Ease with which a sediment can be excavated or dislodged using the cutting edge of a scoop, bucket, or shovel.

Flowability (slope instability). Facility of a sloped soil deposit to fail at its lowest end and flow into an excavation; the instability of a sloped soil.

b. Removal and transport.

Pumpability. Ease with which a soil slurry can be pumped in a pipeline. Sediment type is only one of the factors influencing the energy needed for pipeline transport of sediments. The required energy depends on the typical grain size of the sediment, defined as d_{50} by Herbich (1992). Greatest slurry fluidity occurs with rounded grains.

Sedimentation rate. Rate at which a particle will settle in still water. A function of grain diameter and the viscosity of the fluid. Assessment of settleability requires knowledge of grain-size distribution (percent silt and percent clay), plasticity of the fines, and salinity of the water.

Bulking factor of redeposited soils. Ratio of the volume occupied by a given amount of soil in a containment area immediately after deposition by a dredging process to the volume occupied by the same amount of soil in situ. Deposition volume of a soil is not constant, but depends on grain-size distribution, flocculation capacity, percentage of fines (silt and clay), and plasticity.

c. Disposal.

Dumpability. Cohesive soils that have a medium to high plasticity index (PI) may adhere to the barge or other equipment during disposal. Granular soils containing fines may bridge and require jetting with high-pressure water streams.

Sedimentation rate. Rate at which a particle will settle in still water. A function of grain diameter; larger particles settle faster. Silt and clay particles take hours or days to settle through the water column.

Compactability. Machine compaction to a specification limit in a land disposal area requires either granular soil or low-plasticity cohesive soil that has dried to approximately the plastic limit water content. All soils at almost any water content can be densified mechanically, but not to specified limits.

Soil material, mass, and behavior properties

Soil material properties are those of the soil components without reference to their arrangement in a soil mass; i.e., the individual grains, pore water, or other materials present. Soil material identification tests are performed on a sample of soil whose in-situ mass structure has been completely disturbed by remolding. Material properties include grain-size distribution; sedimentation rate in water; plasticity of the fine fraction; angularity, shape, and hardness of coarse grains; specific gravity of grains; color and odor; organic content; and cementation.

Soil mass properties are those relating to the arrangement of the material components. These include the relative positions of the soil grains, their structure, and mass density. Soil material and soil mass properties are independent of each other. Soil mass properties include mass density, water content, degree of saturation, porosity and void ratio, relative density, permeability, and weight-volume relationships.

Soil behavior properties of interest during excavation include cohesion, angle of internal friction, adhesion to steel cutting surfaces (stickiness), tendency to dilate, permeability, and shear strength. Tests of soil strength must be performed on undisturbed samples. The shear strength of a soil is a fundamental engineering behavior property. Laboratory shear test methods in common use are the direct shear test and the triaxial compression test.

The methods for sediment sampling and geotechnical soil test procedures are included in Appendixes A and B, respectively. Appendix B also contains a general description of geophysical test methods.

Procedure for a Geotechnical Site Investigation

A geotechnical site investigation for a dredging project must answer several questions:

a. How many different soil and rock deposits are there within the proposed dredging prism? Where are they located and what is their configuration?

b. What kind of material constitutes each deposit? Which geotechnical properties will characterize each soil deposit? What are the average value and the range in values of each characteristic property?

c. Are the deposits homogeneous, heterogeneous, or do the properties trend in a known or predictable manner?

A typical geotechnical site investigation for a dredging project involves the following steps:

a. A review of all available pertinent information.

b. Based on the available information, development of an initial hypothesis of the geotechnical subbottom profile, including the type, configuration, and geotechnical character of the subbottom soils present.

c. If the available information is sufficient for the project, the site investigation is terminated. If not, then an estimate is made of site variability. If the site variability is not well known, then a geophysical survey may be appropriate.

d. Where appropriate, continuous subbottom information is obtained by geophysical studies using acoustic subbottom profiling or other suitable methods. Ground-truth correlation is required.

e. If the updated geotechnical information is now sufficient for the project, the site investigation is terminated.

f. If the amended subsurface profile estimate is still not sufficient, then a geotechnical physical site-exploration plan is formulated. The number and location of test sites will be dictated by site variability.

g. At each test site, specific depths and methods are selected for sampling and testing the subbottom materials. Sampling depth may be reached by drilling or digging pits. A description and classification is made for each sample.

h. The new geotechnical information is summarized and reviewed for consistency with the previous profile estimate.

i. If the revised subbottom profile estimate is now sufficient for the project, the site investigation is terminated. However, if more information is required, then additional geophysical and/or geotechnical sampling and testing are done. This iteration is continued until a point of sufficiency is reached.

Factors Affecting a Site-Investigation Strategy

The strategy or plan for a geotechnical subbottom investigation must consider three general factors that establish the necessary scope of the study: (a) variability of the natural soil deposits, (b) size of the sampling and testing program, and (c) value of additional information.

Variability of natural soil deposits

The characterization of a single homogeneous soil deposit for a single property (e.g., shear strength) is most effectively done by defining the trend line of local average values and the variability of individual test values about that trend line. Measured test results vary from the average for three reasons: (a) natural variations in the composition of the material, (b) natural variations in the deposition process, and (c) variations due to the sampling and testing process.

Regression analysis is used to evaluate the nonrandom trend relationship between data pairs. A horizontal or slightly sloping regression line shows uniformity with distance. A steep line demonstrates a fairly rapid change in soil character; this might occur in a beach deposit. A rapid change in the slope or position of a fitted line with distance indicates a facies or material-type change. This might occur laterally in a river bend or in a river delta.

Size of sampling and testing program

The amount of information needed to reduce uncertainty in site characterization to an acceptable level is a function of the complexity of the soil deposits at the site. If the entire project consisted of one soil type with a uniform set of properties and no variation with distance, then only one sample would need to be tested. As site characteristics become more complex, the amount of site-investigation effort (i.e., the number of borings and samples) needed to reduce uncertainty increases. There is a maximum to the curve of amount of site-investigation effort that is useful versus complexity of site properties. If the site is highly complex and heterogeneous, the amount of necessary site-investigation effort drops because no reasonable amount of site exploration can characterize the site adequately. In that case, there need only be sufficient

site-investigation effort to establish, to a reasonable level of certainty, that the site is highly complex. The dredging contractor bid amount will be increased accordingly.

Value of additional information

In preparing a bid, the dredging contractor is faced with risks from a number of unknowns, including weather, personnel, and equipment. The risk factors also include geotechnical risk (i.e., soil types to be encountered, difficulty of dredging them, cost of mobilization of the wrong equipment for the soil types, and cost of pursuing a claim of changed conditions). Hence, all contractors must include in their bid price a cost of anticipated risk, including the geotechnical risk.

If a dredging project is offered for bid with only minimal geotechnical knowledge available, then a cost associated with geotechnical risk will be part of the total project cost as reflected in the bid price. Alternatively, assume that a very extensive geotechnical site investigation has been made: so extensive that the knowledge of the soil profile could be called perfect. The contractor now has all knowledge beforehand needed to match equipment to soil type and character; to schedule equipment; and to determine fuel, personnel, and wear costs. There is absolutely no risk in the project due to lack of knowledge of the characteristics of the soils in the dredging prism. This savings in bid price is the value of perfect information and represents an upper limit of project savings due to the availability of complete geotechnical information.

Every piece of information derived from sampling and testing at the site is added to the total prior information available before the next episode of sampling and testing. In a relationship similar to a learning curve, the initial sample data increase the contractor's knowledge about the site by a large amount and help reduce the risk due to uncertainty about the project soils, and thus reduce the amount of the contract bid price. The amount that the site-investigation information reduces the total project cost, including the bid price and the total cost of claims, is the value of sample information. All new sample data add to total knowledge of the site, but with decreasing value. Information becomes increasingly costly to obtain, and the value of the sample information curve ultimately becomes asymptotic to the value of perfect information.

If the cost of obtaining geotechnical site information is a linear function of the value of that information, then the optimum level of site investigation occurs where the cost of obtaining the geotechnical information intersects the value of the sample information curve on a plot of project cost versus amount of pertinent information.

Implementing a Site-Investigation Strategy

The practical development and implementation of a site-investigation strategy for a dredging site involve making decisions to answer the following specific questions:

a. What should be the scope of the investigation?

(1) Is existing information about the subsurface condition at the site sufficient?

(2) Will a geophysical exploration be useful?

(3) Are sampling and/or testing at field exploration sites needed?

(4) If a field investigation is needed, how many individual exploration sites should be used?

(5) Where should the exploration sites be located?

b. What should be done at each individual exploration site?

(1) How many samples and/or field tests should be made in the vertical reach?

(2) What kind of samples and/or field tests should be made?

(3) Would a boring or a test pit be used? If a boring, what kind of boring?

(4) What kind of work platform should be used?

(5) Which laboratory tests should be made on the samples?

(6) Will all samples be laboratory tested? If not, which criteria will be used to describe/classify them?

The development of a site-investigation strategy is typically done by the owner's organization without consultation with the dredging contractors interested in bidding the job. It is unrealistic to expect the contractor to take risks due to incomplete knowledge about the soil characteristics. The sensible objective should be to provide all contractors with a sufficient amount of geotechnical site information so that the only factors determining who gets the job are capability to manage personnel, equipment, scheduling, and financing. An adequate site investigation is a matter of the contractor's personal aversion to risk.

3 Geotechnical Descriptors for Sediments to be Dredged[1]

Soil properties data can be communicated in two basic ways: (a) raw numerical soil-identification test data, and (b) descriptors. Webster's Dictionary defines a descriptor as: "A word or phrase (as an index term) used to identify an item...especially in an information retrieval system; also: an alphanumeric symbol used similarly" (Spigolon 1993a). Numerical test data can be communicated easily using computer database methods. However, this method does not indicate or infer dredgeability directly. Descriptive terms provide word equivalents to the numbers resulting from soil-identification tests. When numerical definitions for the words are consistent, word descriptors are practical for communicating information.

Descriptors for dredging-related soil properties can be either (a) descriptive terms (words or phrases), (b) an arrangement of soil properties into classification groups with each group representing an assessment or rating of dredgeability, (c) test results from a specific test device or suite of devices, or (d) some combination of these. Spigolon (1993a) proposed consistent descriptive terms for sediments to be dredged.

Classification indicates a rating or grouping of soil properties into predefined classes according to expected or potential behavior in service. Spigolon (1993) also proposed a Dredging Classification System that considered each of the dredging processes: (a) excavation, (b) removal, (c) transport, and (d) deposition, as well as all types of dredging mechanisms and equipment. Eight sediment categories were defined.

[1] Chapter 3 was extracted from Spigolon (1993a), Leshchinsky (1994), and Richter and Leshchinsky (1994).

Descriptive Terms for Properties of Undisturbed Soil Mass

Undisturbed soil properties are those relating to the arrangement of the material components of a soil mass. The properties of the soil materials and the properties of the soil mass are independent of each other. Basically, the mass properties are measures of the strength of the soil. They include angle of internal friction, cohesion, adhesion to cutting surfaces, and permeability. Generally, the denser a soil, the greater the strength and the lower the permeability.

Strength (compactness) of granular soils

The shear strength of granular soils, measured by the angle of internal friction, derives from grain-to-grain contact. The direct measurement of friction angle may be made in the laboratory using either a direct shear test or a triaxial compression test. Undisturbed sampling of cohesionless soils is practically impossible; therefore, the laboratory tests are made on re-densified samples. This requires that in-situ density be known and be reproduced exactly, a condition that also is difficult to accomplish.

Correlations have been developed between angle of internal friction and relative density for cohesionless soils. The determination of relative density requires measurement of in-situ density and the performance of a laboratory procedure for determination of the maximum and minimum densities possible for the same soil. Because it is extremely difficult to obtain an undisturbed sample of granular material from a test boring for density testing, direct determination of relative density, except on surface soils, is virtually impossible. As a consequence, two field tests that correlate reasonably well with relative density have been developed. The most widely used of these is the Standard Penetration Test (SPT). The definition of terms based on percent relative density derived from the SPT is presented by Gibbs and Holtz (1957), Table 1. This terminology appears to be almost universally accepted.

Strength (consistency) of cohesive soils

The shear strength of cohesive soils is derived from inter-particle forces rather than grain-to-grain contact. For a given cohesive soil, the strength is a direct function of density and of stress history. At the high strain rates encountered in dredging excavation, undrained shear conditions prevail. The simplest and most-used measure of the shear strength of cohesive soils is unconfined compressive strength. There are several descriptive terms for defining the unconfined compressive strength of cohesive soils using relative consistency as the basis. Two of the most common, the Unified Soil Classification System (USCS, as presented by Headquarters, U.S. Army Corps of

Table 1
Compactness of Sands Based on Standard Penetration Test (after Skempton (1986))

Term	Relative Density, percent	Normalized[1] SPT N-values		
		Natural Deposits[2]	Recent Fills[2]	Laboratory Test Fills[2]
Very loose	0-15	0-3	0-2	0-2
Loose	15-35	3-8	2-6	2-5
Medium (firm)	35-65	8-25	6-18	5-16
Dense	65-85	25-42	18-31	16-27
Very dense	85-100	42-58	31-42	27-37

[1] Corrected to 60 percent of free-fall energy of standard hammer weight and drop and normalized to unit effective overburden pressure of 100 kPa (1 Tsf).[3]

[2] Natural deposits have been in place (undisturbed) for over 100 years. Recent fills have been in place for about 10 years. Laboratory test fills have been in place for less than 1 month.

[3] A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page vii.

Engineers (HQUSACE) (1960)) and the Permanent International Association of Navigation Congresses (PIANC 1984) Soil Classification System, are shown in Table 2.

Table 2
Consistency of Cohesive Soils

Consistency Term	Unconfined Compressive Strength		
	USCS (HQUSACE 1960)		PIANC (1984)
	Tons/sq ft	kPa	kPa
Very soft	<0.25	<25	<40
Soft	0.25 - 0.50	25 - 50	40 - 80
Medium (firm)	0.50 - 1.00	50 - 100	80 - 150
Stiff	1.00 - 2.00	100 - 200	150 - 300
Very stiff	2.00 - 4.00	200 - 400	
Hard	>4.00	>400	>300

In-situ density of sediments

There are no generally used descriptive terms for in-situ density. Bulk density is typically stated in numerical terms, either as pounds per cubic foot, kilograms per liter, or grams per liter. Values calculated from density, water content, and specific gravity of grains include porosity, void ratio, and gas content. These values also are expressed as numbers rather than as descriptors.

In-situ structure of cohesive soils

The in-situ or undisturbed structure of a cohesive soil cannot be easily described using numbers. Yet, it is essential in understanding the probable behavior of a soil to know if a soil deposit is homogeneous, contains lenses of dissimilar soil, is laminated, or is stratified. The structure of cohesive soils consistency terms is presented in Table 3.

Descriptive Terms for Properties of Soil Material

Soil material properties are those of the soil components without regard to their arrangement in a soil mass (i.e., without regard to the properties of the individual grains, the pore water, or the other materials present). Soil tests are performed on a representative sample of soil whose in-situ mass structure has been completely disturbed.

Grain-size distribution

The primary reason for describing the grain-size distribution of a soil for dredging purposes is to define maximum size, median size, and uniformity. Descriptive terms for defining grain-size characteristics are of value only if they provide the desired information. The use of specific numerical grain sizes to define the terms gravel, sand, silt, and clay has been part of every textural classification system for over 80 years, but there has never been general agreement on the definitions. Several grain-size classification systems are shown in Table 4. The lack of general agreement between the USCS's commonly used in the United States, including the Corps of Engineers, and the European definitions (PIANC 1984) are clearly shown.

Primary soil name

Using a grain-size distribution, a primary name can be determined using the frequency or percentage present of any primary soil group (i.e., boulders, cobbles, gravel, sand, silt, or clay) or one of its subdivisions if the soil is primarily coarse-grained, and naming the soil after the largest group. Another approach to defining the primary soil name is to use the median grain size D_{50}. The

Table 3
Undisturbed Structure of Cohesive Soils

Term	Descriptive Details
Banded	Alternating layers in residual soils.
Blocky	Brittle failure into discrete blocks.
Concretion	Hard inorganic mass different from surrounding soil.
Fissure	Crack, as from shrinkage or frost.
Homogeneous	Uniform properties, such as the same color, texture, and appearance.
Jointed	Regular, parallel cracks.
Laminated	Repeating alternate layers less than 1/4 in. (6 mm) thick.
Lens	Layer, thick in middle and thinning toward edges.
Nodular	Having small, round concretionary bodies.
Slickensides	Former failure (slippage) planes.
Stratified	Alternating layers of different soils (or color)
(a) Parting	(a) 0- to 1/16-in. (0- to 2-mm) thickness.
(b) Seam	(b) 1/16- to 1/2-in. (2- to 13-mm) thickness.
(c) Layer	(c) 1/2- to 12-in. (13- to 300-mm) thickness.
(d) Occasional	(d) one or less per ft (30-cm) thickness.
(e) Frequent	(e) More than one per ft (30-cm) thickness.
Stratum	Layer greater than 1-ft (30-cm) thick.
Varved	Alternating thin layers of silt and clay, usually found in present or former lake bottoms.

fine-grained fraction of a soil should only be distinguished, silt from clay, using the Atterberg plasticity tests.

Modifiers to primary soil name

Virtually all natural soils are a mixture of various sizes. The PIANC (1984) classification system requires some form of word description using adjectives and/or suffixes. The objective of the adjectives to the primary noun is to describe the uniformity of grain sizes by indicating the relative amounts of the various grain-size fractions. The American Society for Testing and Materials (ASTM) (1992) requires that a word description be used to supplement the symbols and that the words include modifiers. Table 5 gives some definitions of soil name modifiers from the published literature. It is evident that there are no general rules for adjectives or suffixes.

Table 4
Grain-Size Classification System

Group Name	Screen Opening, mm (U.S. Standard Sieve Size) Defining Upper Limit of Group			
	Wentworth (1922)	Al-Hussaini (1977)	USCS (ASTM 1992)	PIANC (1984)
Boulder	--	--	--	--
Cobble	256	--	300 (12 in.)	200
Coarse gravel	64	75 (3 in.)	75 (3 in.)	60
Medium gravel	16	19 (3/4 in.)	--	20
Fine gravel	8	4.76 (No. 4)	19 (3/4 in.)	6
Coarse sand	2	2.00 (No. 10)	4.76 (No. 4)	2
Medium sand	0.500	0.850 (No. 20)	2.00 (No. 10)	0.600
Fine sand	0.250	0.212 (No. 70)	0.425 (No. 40)	0.200
Coarse silt	0.063	0.074 (No. 200)	0.074 (No. 200)	0.060
Medium silt	0.031	0.074 (No. 200)	0.074 (No. 200)	0.020
Fine silt	0.016	0.074 (No. 200)	0.074 (No. 200)	0.006
Clay	0.004	0.002	0.002	0.002

Plasticity of cohesive soils

The Atterberg limits reflect the mineralogy and surface chemistry of fine-grained soils (silt and clay), which are major factors in determining cohesive soil behavior. Although they are of value stated numerically, a word description to convey a general experience with similar soils is often useful. Table 6 contains descriptive terms used for the various liquid limit fractions. The symbols shown are intended to be used as in the USCS as modifiers for the two terms silt (M) and clay (C).

Angularity, shape, and hardness of coarse grains

The angularity, shape, and hardness of coarse grains is a factor in pumping energy requirements and in equipment wear. The simplest and most straightforward determination of angularity, shape, and hardness is given by ASTM (1992). That document contains photographs for visual identification of particle angularity by comparison. Soil angularity is classified as: rounded, subrounded, subangular, and angular according to Table 7. Grain shape is defined as: flat, elongated, or flat and elongated as shown in Table 8. When gravel-size particles are struck a strong blow with a hammer, hard particles do not crack, fracture, or crumble. A more detailed definition of these terms is not of great value in dredging-related activities.

Table 5
Soil Name Modifiers

Modifier Term	Percent of Total Sample: Burmister (1951)	Sowers (1979)	ASTM D2487 (ASTM 1992): Coarse-Grained	ASTM D2487 (ASTM 1992): Fine-Grained	Visual-Manual ASTM D2488 (ASTM 1992)
Adjectives to Primary Name					
Trace	1-10	0-15			0-5
Few					5-10
Little	10-20				15-25
Some	20-35	16-30			30-45
Suffix to Primary Name					
With			≥15 sand or gravel	15-29 coarser than No. 200	
Sandy or gravelly				≥30	
Sandy or gravelly		31-45			
And	35-50	45-50			
Mostly					50-100

Table 6
Plasticity Groups for Cohesive Soils

Plasticity Term	Symbol	Liquid Limit, percent: Casagrande (1948)	Dumbleton (1968)	USCS ASTM (1992)	Carrier (1988)
Nonplastic	N		<20		
Low	L	0-35	20-35	<50	0-35
Intermediate (medium)	I	35-50	35-50		35-50
High	H	>50	50-65	≥50	50-100
Very high	V		65-80		100-150
Extremely high	E		>80		
Ultra high	U				150-200
Super high	S				>200

Table 7 Angularity of Coarse-Grained Particles (after ASTM (1992))	
Term	**Criteria**
Angular	Particles have sharp edges and relatively plane sides with unpolished surfaces.
Subangular	Particles are similar to angular description but have rounded edges.
Subrounded	Particles have nearly plane sides but have well-rounded corners and edges.
Rounded	Particles have smoothly curved sides and no edges.

Table 8 Shape of Coarse-Grained Particles (after ASTM (1992))	
Term	**Criteria**
Flat	Particles with width-to-thickness ratio greater than 3.
Elongated	Particles with length-to-width ratio greater than 3.
Flat and elongated	Particles meeting criteria for both flat and elongated.
Spherical (typically not stated in description)	Particles having width-to-thickness ratio and length-to-width ratio less than 3.

Soil color

Soil color, while not of great consequence in the dredgeability of soils, is of considerable help in correlating soil samples from location to location during geotechnical analysis of the site investigation. Soil colors are often useful in (a) detecting different strata, (b) defining soil type based on experience in a local area, and (c) possible identification of materials. Soils that are dark or drab shades of brown or grey or almost black are typically organic. However, the black color of some soils results from mineral content. Brighter colors are associated with inorganic soils. Red, yellow, and yellowish brown suggest iron oxide, whereas white or pink indicate silica, calcium carbonate, or aluminum compounds. The standard group of colors used in current Corps of Engineers documents is given in Table 9.

Organic content

Sediments may contain organic matter that will affect the excavation and pumping process. Organic content of a soil sediment may be established in the laboratory by dry or wet combustion or by the Atterberg limits procedure. Ash content is the uncombusted residue, mostly clay minerals, after the sample has been dried at a sufficiently high temperature to burn all the organics. The description of highly organic soils is given in Table 10.

Table 9
Suggested Standard Soil Colors

Color	Symbol	Color	Symbol
Tan	T	Brownish-gray	br Gr
Yellow	Y	Grayish-brown	gy Br
Red	R	Greenish-gray	gn Gr
Black	Bk	Grayish-green	gy Gn
Gray	Gr	Green	Gn
Light gray	lGr	Blue	Bl
Dark gray	dGr	Blue-green	bl Gn
Brown	Br	White	Wh
Light brown	lBr	Mottled	Mot
Dark brown	dBr	Reddish	rd

Table 10
Highly Organic Soils (after Landva (1986) and ASTM (1992))

Soil Type	Description
Peat	Ash content less than 25 percent. Derived from plants. Very fibrous.
Peaty organic soils	Ash content 25 to 40 percent. Part fiber and part colloidal organics.
Organic soils	Ash content 40 to 95 percent. All colloidal organics.
Soils with organic content	Ash content over 95 percent. All colloidal organics.

Cementation

Granular and mixed-grain soils may be cemented with various natural cementing agents. The only cementing agents for which descriptive terminology has been developed are those that will react with hydrochloric acid, mostly calcium carbonate (limestone) or calcium oxide (lime), given in Table 11.

Table 11
Reaction of Sediments with Hydrochloric Acid (HCl) (after ASTM (1992))

Description	Criteria
None	No visible reaction.
Weak	Some reaction, with bubbles forming slowly.
Strong	Violent reaction, with bubbles forming immediately.

Descriptive Terms for Properties of Granular Sediments

Descriptors characterizing the dredgeability of granular soils were developed by Leshchinsky (1994). The descriptors were related to the effective shear strength of granular soils. This strength is a result of both the effective angle of friction and indirectly the coefficient of permeability of the soil. Permeability is used as a measure indicating the ability of the soil to dissipate excessive pore-water pressure developing during dredge cutting. Consequently, permeability affects the shear strength of the soil when rapid shear (i.e., dredge cutting) is applied and thus influences the dredgeability.

A step-by-step procedure to determine the descriptors was presented by Leshchinsky (1994). It includes field tests to estimate in-situ density and water content, as well as simple laboratory tests to identify the soil and its maximum/minimum densities. As a result, the relative density of the soil, including gravel, sand, and silt, can be estimated. By modifying existing correlations commonly used in foundation engineering, shear strength and, subsequently, descriptors for dredgeability, were established. To verify the value of this descriptor in sandy soils, conducting either SPT or Cone Penetration Tests (CPT) is recommended. Since these two tests are less direct in defining the descriptor as compared to field measurement of density, the SPT and CPT are considered to provide only supplemental information. The SPT or CPT only should be used if the site consists of sand.

The descriptors of Table 12 have been developed based on fundamental concepts in soil mechanics. However, they contain a conversion that is based

Table 12
Descriptors Associated with Dredge Cutting Difficulty for Granular Sediments

	Dredging Difficulty Rating[1]			
	Permeability			
Angle of Internal Friction	High	Medium	Low	Condition
Less than 25°	1	1	1-2	Very loose
25° - 30°	2	2	2-3	Loose
30° - 35°	3	2-3	3-4	Medium
35° - 39°	4	3-4	4-5	Dense
Greater than 39°	5	5	5	Very dense

[1] Descriptors Equivalent to Dredging Rating:
1 = Very easy
2 = Easy
3 = Normal
4 = Difficult
5 = Very difficult

on judgement (i.e., physical properties of granular soils are converted into a qualitative scale of anticipated difficulty associated with dredge cutting). It should be pointed out that there is insufficient relevant experience in the dredging discipline to verify the accuracy of the scale chosen for the descriptors. Therefore, it was recommended by Leshchinsky (1994) that the descriptors be used as a basis for future adjustment and refinement in conjunction with actual dredging operations, applying the suggested procedure for determination of the difficulty rating. Special attention should be given to silty soils.

Degradation of Hydraulically Transported Clay Balls

Clay balls and friction loss

Materials that are difficult to cut (i.e., boulders or cobbles) are best removed by mechanical dredging means such as the bucket or clamshell dredge. Extremely loose soils are best removed by a pure suction dredge such as a dustpan or hopper dredge. Cohesive or dense soils are most efficiently cut and moved by the suction cutterhead dredge.

Friction losses and energy expended by transporting material through a pipeline are greatly dependent on the type and rate of dredged material being hydraulically transported. Cohesive soils excavated by the cutterhead typically move into a pipeline as lumps. Similar to noncohesive soils, cohesive ones also are transported through the pipeline by fluid velocity and turbulence. However, unlike sand, if the lumps are not friable, they will be carried as a moving bed in the bottom of the pipe.

Because moving bed flow is less efficient than suspended particle flow, intake of clay materials must be reduced to keep friction and adhesion losses low enough to maintain flow. If the clay is sticky, it may clod and create clay balls (i.e., particles may adhere to each other). As a result, clay materials are typically transported at 4 to 5 percent by volume of in-situ material to the total flow in the pipeline. However, some clays begin to slurrify as they are transported, resulting in a decrease in friction loss, thus allowing a higher percentage of solids.

Experimental program

A method for determining degradation of clays undergoing hydraulic transport was developed by Richter and Leshchinsky (1994). This method is based upon experimental test results, using simulated clays, exposed to dredge-like conditions. The simulated clays were prepared under controlled conditions in the laboratory, to study the effect of PI and relative compaction (R_c) on degradation. The simulated clays were produced using different proportions of bentonite and kaolinite in the mixture. This allowed clays with widely varying

PI to be formed. The clays were then tested at different compaction levels as related to maximum standard Proctor. This form of expressing compaction is useful because it makes consistent comparisons with any other soil through a standardized test.

The results of the testing program clearly show that plasticity and relative compaction have significant effects on rate of degradation. For heavily compacted material (near 100 percent of maximum standard Proctor), the rate of degradation was found to be nearly zero for any PI greater than 25 percent. For lightly compacted clay, the rate of degradation was found to be a function of plasticity. Rates of degradation for light to moderately compacted clays with PI between 25 and 35 percent was rather slow. As plasticity increases above PI = 35 percent, however, rate of degradation became negligible. Hence, clay balling is likely to occur when a PI is greater than 35 percent. Conversely, slurrification of dredged clay lumps is likely to occur when a PI is less than 25 percent.

Design guidance degradation prediction

The degradation effects on the tested clays caused by hydraulic transport have been conveniently presented in the form of design charts. This allows predictions regarding degradation to be easily made based on simple and relevant geotechnical properties of the clay to be dredged. These design charts are presented in Figures 1-3. To use the charts, three properties of the soil to be dredged must be determined, and the hydraulic conditions under which it will be transported must be known. The soil properties needed are the PI of the soil, the maximum standard Proctor dry density of the soil, and the field dry density of the clay, which is a measure of how compact the soil is in its natural state.

Determination of these properties is a simple and relatively inexpensive process. The hydraulic transport condition needed to make degradation predictions is the velocity of the transport fluid relative to the velocity of the clay lumps. This can be estimated as the pipeline discharge rate (i.e., cubic yards of liquid per hour) minus the excavation (production) rate (i.e., cubic yards of clay excavated per hour), divided by the pipe cross-sectional area.

The results presented by Richter and Leshchinsky (1994) have important applications for the dredging industry because they can be used to predict the behavior of dredged clay. These results provide a rational link between the geotechnical characteristics of clays and the behavior of the material when dredged and transported by cutterhead pipeline methods.

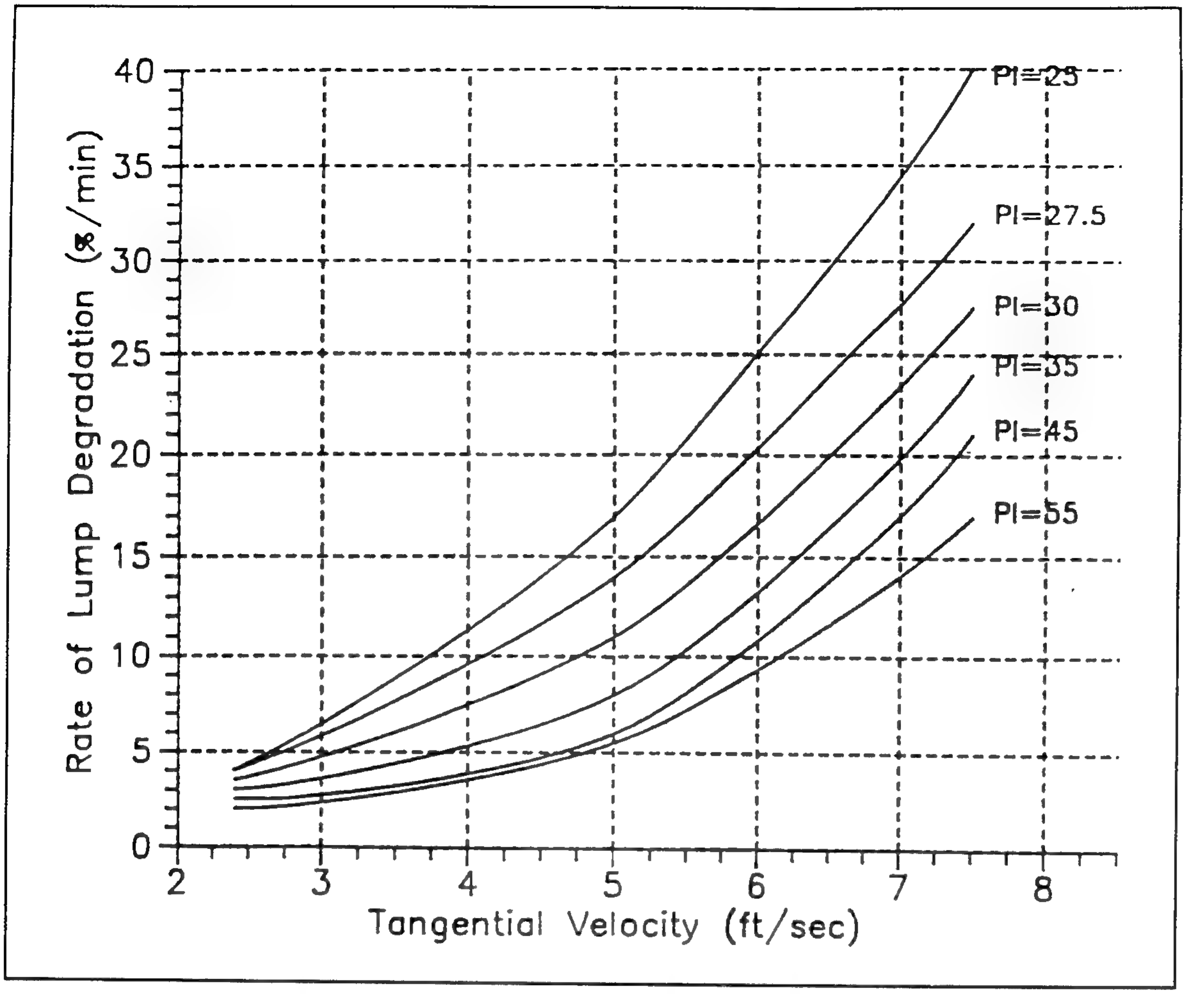

Figure 1. Rate of clay ball degradation versus relative velocity of transport fluid at relative compaction = 80 percent (after Richter and Leshchinsky (1994))

Proposed Dredging Sediment Classification System

Soil classification systems have been established, and are described in the geotechnical engineering textbooks, for various construction-related uses to rate (i.e., indicate suitability of) soils for use in a specific application. Most systems utilize the soil material properties of the disturbed soil as the basis for class grouping without concern for the original in-situ mass properties because the systems were developed for application to the use of the soil as a construction material. None of the existing systems indicates dredgeability either directly or indirectly because none of them include the in-situ strength in the classification or directly address any other needs of the dredging disposal process.

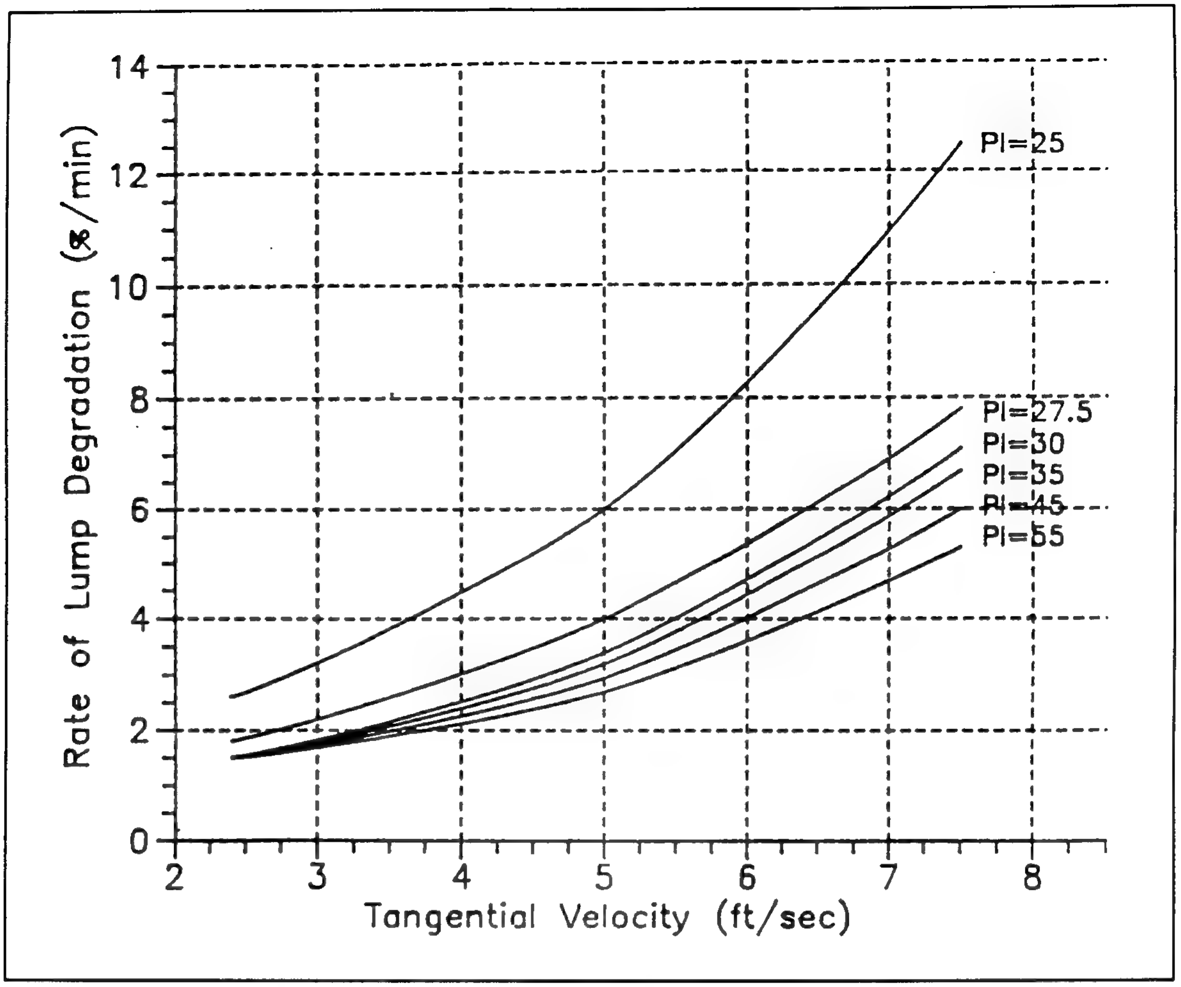

Figure 2. Rate of clay ball degradation versus relative velocity of transport fluid at relative compaction = 90 percent (after Richter and Leshchinsky (1994))

A classification system for directly indicating or inferring the dredgeability of in-situ sediments should be based on dredgeability properties:

a. Excavation properties: suctionability, erodability (scourability), cuttability (affected by friability), scoopability, and flowability (underwater slope stability).

b. Removal and transport properties: pumpability (affected by rheologic properties of slurry), abrasability (abrasiveness in a pipeline), clay balling (affected by stickiness), sedimentation rate in a hopper, and amount of bulking.

c. Disposal properties: dumpability (affected by friability and stickiness), sedimentation rate in a disposal area, amount of bulking, and compactability.

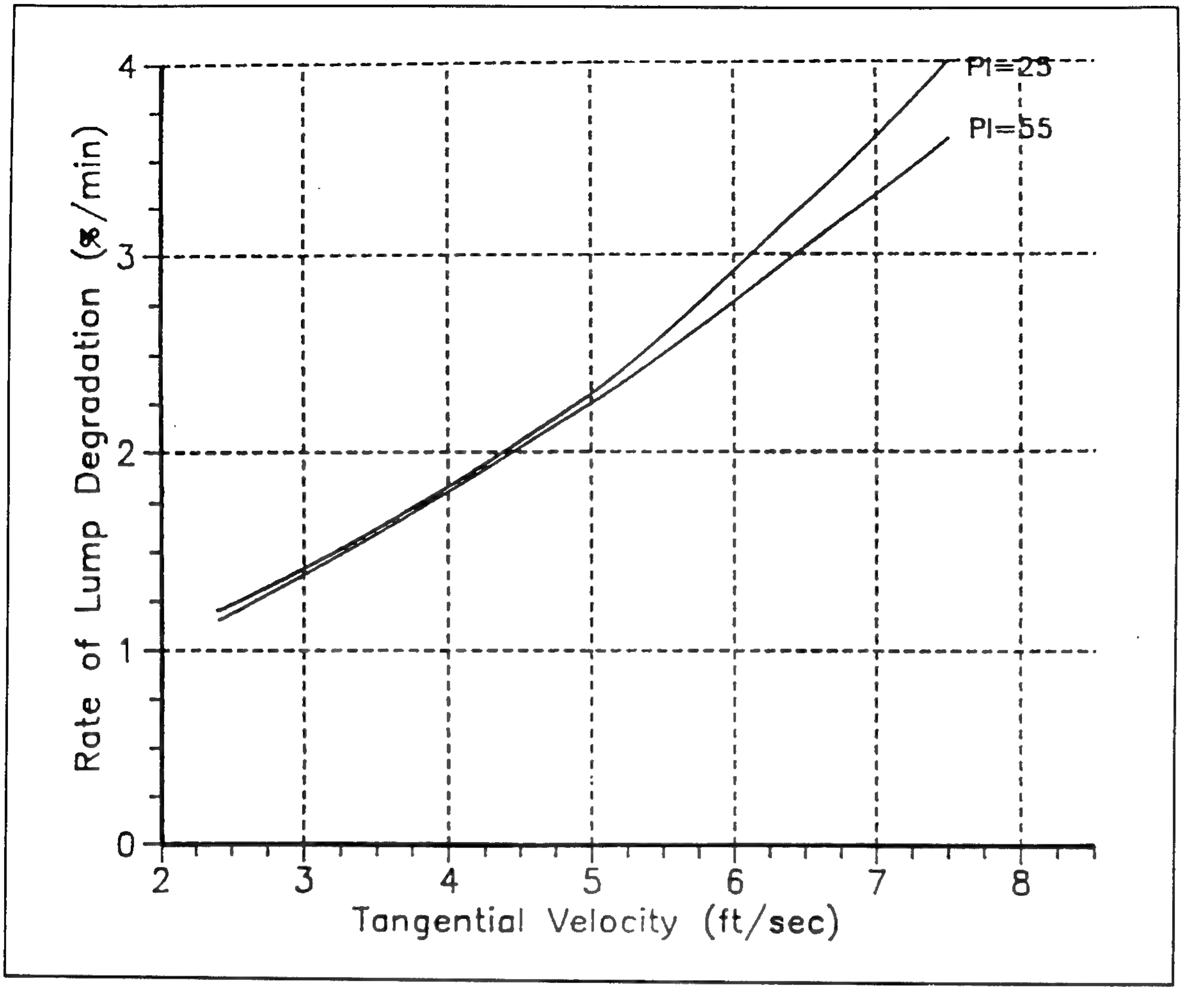

Figure 3. Rate of clay ball degradation versus relative velocity of transport fluid at relative compaction = 100 percent (after Richter and Leshchinsky (1994))

It has been suggested by Spigolon (1993a) that sediments be placed in the eight groups shown in Table 13, each group with different fundamental dredging characteristics. New work may encounter any of the eight groups. Maintenance dredging will deal mainly with Groups G, F, and M. It is assumed that rock, shale, or cemented sediment has been pretreated by blasting, ripping, or other suitable method. At that point, the material becomes a group of broken angular fragments and can be dredged using standard dredging equipment systems.

Table 13
Proposed Dredging Sediment Classification System

GROUP R: Rock and Coral	
Geotechnical Properties	Rock is massive, solid (nongranular), inorganic mineral matter with an unconfined compressive strength exceeding 1,000 kPa (10 Tsf). Coral consists of living calcareous organisms usually formed into a massive offshore reef.
Excavation Properties	Hard rock and coral require blasting to break the mass into fragments that can be removed by normal dredging equipment. Softer rock and coral can be easily cut or ripped into small fragments. Cut slopes are stable.
Removal and Transport Properties	Blasted or ripped rock fragments behave like Group B, "boulders and cobbles." Hard rock fragments can be abrasive in pipelines.
Disposal Properties	Blasted or ripped rock fragments behave like Group B, "boulders and cobbles."
GROUP S: Shale and Cemented Soils	
Geotechnical Properties	Highly compressed clays (shale) or rocklike soils cemented with iron oxide, lime, silica, calcium, or magnesium; have unconfined compressive strength below that of rock.
Excavation Properties	Requires cutting, ripping, or blasting; usually breaks up into small particles. Cut slopes are stable.
Removal and Transport Properties	Fragments can be removed and transported using either hydraulic or mechanical methods; energy requirement is function of fragment size distribution. Hard angular fragments can be very abrasive in pipeline.
Disposal Properties	Behavior similar to cobbles or coarse gravel; shale fragments may soften appreciably in air or water.
GROUP B: Boulders and Cobbles	
Geotechnical Properties	Material is dominantly blasted rock fragments or natural boulders and cobbles; deposit typically contains mixture with gravel, sand, and fines; usually insignificant amounts of nonplastic fines. Usually dense and shear strength derives almost entirely from grain-to-grain contact.
Excavation Properties	Usually excavated by mechanical methods (scooping). Hydraulic methods are usually inefficient.
Removal and Transport Properties	Not easily moved hydraulically. Requires high velocity/high volume hydraulic removal methods or mechanical (bucket) removal and transport methods.
Disposal Properties	Dumping is easy and coarse particles settle very fast. Very difficult to compact beyond dumped density because of grain-to-grain contact. Low bulking factor.
GROUP G: Clean Granular Soils	
Geotechnical Properties	Material is gravel, sand, or coarse silt with little or no plasticity; will not stand unconfined if dry. Shear strength derives from relative density, grain angularity, and lack of fines.
Excavation Properties	Excavates easily under hydraulic erosion (scour). Has high friability. Easily cut or scooped. Slopes not stable; tend to flow easily to angle of underwater repose.

(Sheet 1 of 3)

Table 13 (Continued)	
Removal and Transport Properties	Easily removed and transported hydraulically. Particles settle very quickly in a hopper. Readily transported in a pipeline slurry; energy required is function of median grain size. Large particles contribute to pipeline wear. Bulking factors are low.
Disposal Properties	Dumps easily. Settles quickly in disposal area. Clean granular soils (few or no plastic fines) will densify with vibration. Typically does not respond well to mechanical compaction.
GROUP F: Friable Mixed-Grain Soils	
Geotechnical Properties	Material is mixed-grain soils or low plasticity friable soils, such as small gravel, sand, silt with appreciable clay content. Strength derives from combination of grain-to-grain friction and cohesion due to clay. Friable due to low plasticity of -No. 40 fraction.
Excavation Properties	Not easily suctioned; too dense or too much clay for easy erosion; typically suitable for cutting or ripping process. Easily scooped. Well suited to cutter suction or bucket-wheel suction process. Underwater slopes do not flow easily; are fairly stable.
Removal and Transport Properties	The soil is friable and will disintegrate during excavation and hydraulic removal; will enter easily into a pipeline slurry. Clay balling is normally not encountered. Sedimentation rate in hopper is typically fast, although disintegrated fines may not settle quickly.
Disposal Properties	Usually will respond well to mechanical compaction but not to vibration.
GROUP C: Cohesive Soils	
Geotechnical Properties	These are massive fine-grained soils, typically firm to hard clays and silty clays of medium to high plasticity. Not friable. Have sufficient density and clay content to have unconfined compressive strength. Exhibit plasticity, cohesiveness, and dry strength. Little or no grain-to-grain contact; shear strength derives from density, stress history, and amount and type of clay.
Excavation Properties	Not friable (will not crumble easily); will not suction or erode; may be excavated using cutting or scooping. Underwater slopes are usually stable except for very soft clays.
Removal and Transport Properties	Probably form clods during mechanical transport or clay balls in hydraulic pipeline. Low abrasion in pipeline. Will not settle rapidly in hopper; will usually overflow.
Disposal Properties	Often sticky when water content is high. Take appreciable time to settle in land disposal area. The cohesiveness of the clay prevents the soil from densifying with vibration. Bulking is fairly high.
GROUP O: Highly Organic Soils	
Geotechnical Properties	Peat, humus, and swamp soils are examples. Typically has a spongy consistency, a high water content, and dark brown to black color, although color alone is not an indicator. Usually has an organic odor in a fresh sample or in wet sample that has been heated. Has a fibrous to amorphous texture and often contains vegetable matter (sticks, leaves, etc.).
	(Sheet 2 of 3)

Table 13 (Concluded)

Excavation Properties	May be cut or scooped. Behaves like a soft to firm cohesive soil (Group C), unless fibrous matter interferes with cutting.
Removal and Transport Properties	High gas content may interfere with hydraulic suction. Fibrous matter content may interfere with pipeline transport. Easily moved mechanically.
Disposal Properties	Organic matter is not usually desirable in a disposal area. Ocean disposal may leave some fibrous matter floating or in suspension. Not easily compacted because of sponginess.
GROUP M: Fluid Mud	
Geotechnical Properties	Mud found at or near the surface of the bottom in harbors and other areas of slow current. Extremely low shear strength; has no unconfined compressive strength; physically behaves like a fluid, i.e., sample will not retain its shape. The solids are mainly silt and clay or low to high plasticity, but may have some very fine sand. Invariably has a very low density and very high water content in situ.
Excavation Properties	Easily suctioned at or near in-situ density without dilution water. Erodes easily with very little dilution water added. Will not stand on slope.
Removal and Transport Properties	Easily transported in a pipeline; may require addition of dilution water for improved flowability. Fine grains will not settle quickly in a hopper or in a disposal area.
Disposal Properties	Fine-grained soils do not settle quickly in disposal area.
	(Sheet 3 of 3)

4 Geotechnical Evaluation of the Dredgeability of Sediments Using GEODREDG[1]

Geotechnical engineers typically plan and conduct the subsurface investigation of a proposed dredging site. The engineers describe the physical properties of the sediments that appear to be present within the dredging prism. Dredging operations personnel use the geotechnical information in estimating and planning.

Knowledge-Based Expert System (KBES)

Geotechnical engineers, when planning and executing the site investigation, may not be fully aware of the type of information the dredgers need about the sediments to be dredged. Turnovers in personnel or changes in assignments mean that geotechnical engineers with little experience in dredging can become involved in the subsurface investigation and the testing of sediments for dredging projects. Dredging-related knowledge of the more experienced geotechnical engineers is often not adequately transferred and is usually lost through retirement or position change.

Geotechnical engineering descriptions of soils do not indicate so-called "dredgeability" properties directly. All require analysis and interpretation. This leads to possible misinterpretation of sediment-related risks, with resulting higher bid costs, and is often a cause of costly claims.

There is, then, a continuing need for the guidance and training of those persons lacking knowledge and experience in the dredgeability analysis of geotechnical data. It is desirable to retain the expertise of capable persons involved in dredging-related fields and to make their experience available. One highly useful manner of retaining this knowledge and making it available is by means of a computerized knowledge-based expert system (KBES).

[1] Chapter 4 was extracted from Spigolon and Bakeer (1993; 1994a, b, c; in preparation)

A KBES is a computer program for the type of problem that requires expertise in a field or discipline for its solution. Conventional programs generally use algorithmic (repetitive) procedures in a predefined sequence for processing data that are primarily numerical. The information (knowledge) and the method of controlling it are integrated; this inhibits mid-run changes in procedure. A KBES uses expertly derived rules for its solutions; the rules can incorporate and process judgement, experience, empirical rules of thumb, intuition, and other expertise as well as proven functional relationships and experimental evidence.

The knowledge base contains a database of facts and "IF - THEN" rule statements that include all of the "IF" questions a typical user is expected to ask and all of the "THEN" solutions. The control system (inference engine) is independent of the knowledge base. An independent explanation facility, consisting of a series of individually accessible texts on relevant topics, is used to explain the rationale for the rules. The separate knowledge base and explanation facility may be edited and modified without changing the other components of the program.

The components of a typical KBES are:

a. Knowledge base--contains the facts and expert-derived rules associated with the domain (subject matter) of the KBES.

b. User interface--provides for input of problem information as "IF" statements and for the output of "THEN" solutions.

c. Context--contains the information about the problem currently being solved (i.e., the parameters of the problem and information generated by the KBES during solution of the problem).

d. Inference mechanism--uses the context of the problem to search the knowledge base for a solution, or solutions, to the problem.

e. Explanation facility--provides the user with information about the reasoning process and how a solution was reached.

f. Knowledge acquisition facility--an editor providing for creation and modification of the knowledge base.

During a KBES application, the KBES searches the knowledge base through a chain of "IF - THEN" rule statements. The "IF" questions are posed in a series of screens in the user interface. The path through the matrix of rules is not predetermined; rather, the path depends on the specific IF questions and on the generated THEN replies that lead to the next IF statement. The net effect is one of having an expert in a field answering the IF questions with a THEN reply, each presumably leading the user to the next IF question until the solution is reached. The logic of the IF statements may be modified by using such modifiers as AND, OR, or NOT, and the arguments may be

either English words or phrases or numbers. The solution(s) are then displayed by the user interface.

GEODREDG

Spigolon and Bakeer (1993) developed a KBES called GEODREDG to provide access to the recorded expertise and guidance from experts in their respective fields for the use of:

a. Geotechnical engineers in the planning and execution of a subsurface investigation for a dredging project.

b. Dredging estimators and planners for interpreting geotechnical site-investigation data in terms of dredgeability.

GEODREDG consists of two interrelated KBES programs that have been developed as part of an overall system:

a. DREDGABL--guidance in the interpretation of geotechnical properties data for estimating the dredgeability of sediments. Intended to serve the planner or estimator as a personal geotechnical engineering and dredging expert consultant.

b. GEOSITE--guidance for geotechnical engineers and engineering geologists in the selection of methods and equipment for the sampling and strength testing, field and laboratory, of sediments to obtain the information necessary for evaluation of the dredgeability of the sediments.

Expert system shell for GEODREDG

The development of a KBES is greatly facilitated by the use of an expert system shell (development framework). Several of the most commonly used commercial expert system shells were evaluated for use in GEODREDG by Spigolon and Bakeer (1993). Selection criteria included:

a. Hardware compatibility--with the PC-DOS type of personal computer machines.

b. Implementation language--natural English words.

c. Convenient environment--including user interface and explanation facilities.

d. External interface--with databases (dBase III Plus and compatibles) and with spreadsheets (Lotus 1-2-3 and compatibles).

e. Reasonable initial cost and low cost for unlimited run-time versions; stability of vendor and continued availability of user help support.

The system chosen for use in the GEODREDG system was the Microsoft FoxPro Relational Database Management System. All of the necessary facilities for implementing a KBES are available in Microsoft FoxPro, including user interface screens, control programs (inference engine), context storage as memory variables, a spreadsheet-derived database of rules, and an explanation (help) text access system. Once the antecedents (IF statements) are established, the search of the knowledge base (database) is very rapid. The knowledge bases were developed in spreadsheet format and converted to Dbase III Plus format, which is supported by FoxPro. Therefore, the control programs, the explanation texts, and the knowledge base may be operated by other compatible database programs.

There are two other important advantages of Microsoft FoxPro. One is the capability of using the same program in either a DOS or a Windows environment; only the screen format changes because Windows uses a graphical display. The other advantage is the availability of a run-only distribution version. The distributed version can be used for an unlimited number of applications at a single modest fee beyond the cost of the original developer's version.

Both versions of GEOSITE and DREDGABL (DOS and Windows) support either keyboard tab-arrow key selections or mouse input. This practically eliminates the need for the user to type words for data input or for consultations. When running under the Windows environment, the GEODREDG programs provide for graphical displays in the explanation facility that will permit use of line drawings, sketches, and photographs to enhance the text.

Application of GEODREDG

GEODREDG is intended to address the needs of the dredging industry for guidance in describing the physical properties of sediments and assessing their dredgeability. The total GEODREDG expert system shown in Figure 4 works as follows:

a. It is assumed that some prior information, geological and perhaps geotechnical, exists about a proposed dredging site. This may be augmented as appropriate with geophysical exploration data. The preexisting information is used to develop a preliminary estimate of the subsurface geotechnical profile.

b. Based on all the preexisting geotechnical information about the site, a site-exploration strategy is developed, including the number and locations of the exploration sites.

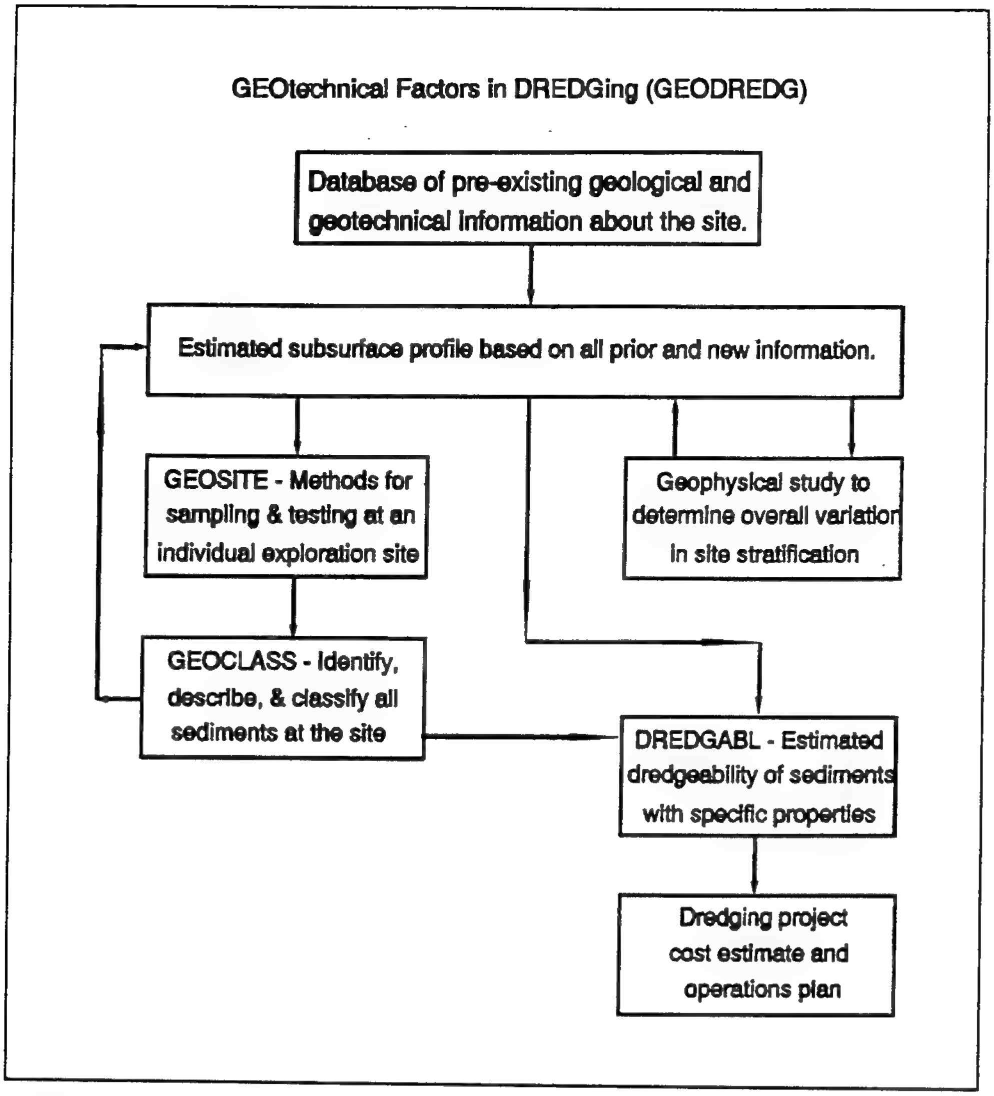

Figure 4. The GEODREDG knowledge-based expert system modules (after Spigolon and Bakeer (1993))

c. The GEOSITE program is used to select suitable sampling and testing methods, a suitable sample/test access method, and a work platform for each site.

d. After completion of the site-exploration program, a complete set of boring logs is prepared that contains suitable sample descriptions and classifications.

e. During the planning of a dredging project, the DREDGABL program is used to provide guidance in the dredgeability properties of each of the sediment types encountered during the site investigation.

GEODREDG will be field evaluated and modified in future versions. Because of the KBES concept, there really is no terminal point for the

programs. The knowledge base(s) and the explanation system for each module can and will increase with time as more and more experts add their knowledge to the system.

GEOSITE

The objective of GEOSITE is to provide guidance from geotechnical engineering experts for the selection of equipment and methods for a subsurface investigation at an individual exploration site for a dredging project. It is assumed that the number and locations of the exploration sites have previously been established and that there is a general knowledge of the types of sediments to be expected at the site. The GEOSITE program recommends: (a) sediment sampling methods; (b) in-situ strength testing methods, considering all of the appropriate sampler/testing method combinations; (c) methods for accessing the sampling/testing depth; (d) suitable field work platforms; and (e) material identification tests. The sediment types expected to be present at any dredging project exploration point include one or more of those of Table 14.

GEOSITE user's guide

The user's guide for GEOSITE, prepared by Spigolon and Bakeer (in preparation), contains explicit detailed instructions for application of GEOSITE to a prototype dredging site and operational instructions for navigating through the GEOSITE program, including:

a. Installation instructions--guidance for placing the Windows version and/or the MS-DOS version of GEOSITE on the user's hard disk.

b. Operating instructions--Each of the data selection (input) display and conclusion display screens is discussed and a description of the discussion (help) screen system is presented.

c. Discussion of background topics--First, there is a general discussion of KBES and the manner in which they function. Second, the rationale for selecting a relational database management system as the expert system development shell is presented. Third, the relationship of a KBES with a printed report is examined.

d. Potential future modifications to the GEOSITE program--The requested review information is intended primarily for use by the programmers and administrators of the development version of GEOSITE.

The GEOSITE User's Guide contains instructions for installing and using GEOSITE. The diskettes for the Microsoft Windows version of GEOSITE are included with each copy of the User's Guide. A limited number of the MS-DOS version are available on request to the Scientific and Engineering

Table 14
Characteristics of Basic Sediment Types Encountered in Dredging Operations

Sediment Types	Characteristics
High Organic Soils	Peat, humus, and swamp soils are typical. Typically have a spongy consistency, a high water content, and dark brown to black color, although the color alone is not an indicator. Usually have an organic odor in a fresh sample or in wet sample that has been heated. Have a fibrous to amorphous texture and often contain vegetable matter (sticks, leaves, etc.).
Cohesive Soils	By definition in the USCS, any soil with 50 percent or more by weight passing the No. 200 screen (D_{50} < 74 microns) is a fine- grained soil. Cohesive fines (silt and clay) dominate engineering behavior. The presence of as little as 20 to 40 percent passing the No. 200 screen is sufficient for a granular soil to behave as a cohesive soil. Has sufficient density to have unconfined shear strength, i.e., will retain the shape of a container. Little or no grain-to-grain contact; shear strength derives from density, stress history, and amount and type of clay. The cohesiveness of the clay prevents the soil from densifying with vibration. Exhibits plasticity, cohesiveness, and dry strength.
Cohesionless Soils	By USCS definition, more than 50 percent by weight of a coarse-grained soil is retained on the No. 200 screen (d_{50} > 74 microns). Maximum size is 76 mm (3 in.). Grain-to-grain contact dominates the engineering behavior. Shear strength derives from relative density, grain angularity, and lack of fines. Clean granular soils (few or no plastic fines) will densify with vibration and will not stand unconfined if dry. Exhibits moderate to high friability.
Cobbles and Boulders	Individual grains between 76 mm (3 in.) and 305 mm (12 in.) are cobbles and those over 305 mm in diameter are boulders. May be rounded from movement in a stream or may be angular rock fragments, either natural or as the result of ripping or blasting of solid rock. Usually dense and shear strength derives almost entirely from grain-to-grain contact.
Cemented Soils and Shale	Rocklike soils cemented with iron oxide, lime, silica, or magnesium or highly compressed clays (shale); have compressive strength below that of massive, hard rock; when cut or ripped, usually fragment into small particles.
Rock or Coral	Rock is massive, solid (nongranular), inorganic mineral matter with an unconfined compressive strength exceeding 10,000 lb per sq in. Coral consist of living calcareous organisms usually formed into a massive offshore reef. Hard rock and coral require blasting to break the mass into particles that can be removed by normal dredging equipment. Softer rock and coral capable of being easily cut or ripped into small fragments.

Applications Center, Information Technology Laboratory, ATTN: CEWES-IM-DS, USAE Waterways Experiment Station, Vicksburg, MS 39180-6199.

Application of GEOSITE

Application of GEOSITE begins with the assumption that the stratification is moderately well known. It is reasonable to require this assumption, which demands that every effort be made to assemble and evaluate existing information and to use geophysical surveys wherever they are feasible. The choice of specific primary sediment types from the expected profile causes GEOSITE to limit its consultation advice only to those topics that apply to the primary sediment types and to exclude all others. If, in the field, the profile expectation is found to be wrong, then a return to the program for reevaluation with the updated information will be necessary.

Four separate exploration objectives are provided in GEOSITE:

a. *Regular investigation.* The regular or complete investigation objective starts with selection of sediment type. This causes GEOSITE to display a screen of all generic sediment samplers and description of their suitability for that sediment type. One of the samplers is selected, and then the next screen displays a choice of field or laboratory (or none) strength testing methods. This choice leads to a screen containing strength test methods and their suitability for the combination of sediment type and sampling method. The screen also displays a confidence factor and a utility factor for each test method. If desired, the contents of this screen may be printed in report form for filing.

If desired, the user may then return to previous screens for advice on a different combination. Or, once a sampler and test method are chosen, further guidance is given for methods to access sampling-testing depth, for field work platforms, and for material information tasks.

b. *Density testing only.* The density-testing-only objective starts with a selection of one of the sediment types expected in the sediment profile. GEOSITE then provides guidance on the suitability of various methods for determining the in-situ density. Most of the methods are different from methods used for sampling and/or strength testing.

c. *Rock surface only.* The rock-surface-only objective starts with selection of the sediment type that forms the overburden for the rock or hard surface to be located. Guidance is then given about the suitability of various methods for locating the surface of rock or a hard layer.

d. *Material identification tests only.* This option is available for the user who simply wants guidance on material identification tests that are appropriate for identifying, describing, and possibly classifying a

disturbed sample. It is also included as part of the sequence of guidance screens in the "Regular investigation" objective.

GEOSITE problem-solving strategy

GEOSITE contains seven knowledge bases: (a) SAMPLING, (b) TESTING, (c) ACCESS, (d) PLATFORM, (e) MATTEST, (f) DENSITY, and (g) ROCKSURF. GEOSITE uses a forward-chaining or data-driven problem-solving strategy. The knowledge representation is rule-based, each rule consisting of an "IF-AND <antecedents>...THEN<conclusion>" statement. One rule exists for each of the total finite number of options in the antecedents.

In the present version of GEOSITE, there are 3,780 rules in the 7 knowledge bases. Ideally, each unique set of antecedent options leads to a single conclusion. In the SAMPLING knowledge base, GEOSITE reaches 9 conclusions (one for each generic sampler type) for each of 8 sediment types, for a total of 72 rules. For each of the 18 generic strength test methods in the TESTING knowledge base, GEOSITE reaches 3 conclusions (suitability, confidence factor, and utility factor), for a total of 54 conclusions for each combination of sediment type and suitable sampler, resulting in 2,754 rules. There are 582 rules in the ACCESS knowledge base, with 6 conclusions for each of 97 combinations of sampling device and testing method. There are 220 rules in the PLATFORM knowledge base, with 5 conclusions for each of 44 combinations of sampler/test method, water roughness, and current strength. The MATTEST knowledge base contains 64 rules, for 8 sediment types and 8 conclusion fields. In the DENSITY knowledge base, there are 48 rules, with 6 conclusions for each of 8 sediment types. And the ROCKSURF knowledge base contains 40 rules, one for each of 8 overburden sediment types with 5 conclusions for each.

Modifying and upgrading GEOSITE

KBES programs such as GEOSITE have no completion point; there is always more knowledge that can be added and there are more conclusions that can be drawn. The program details that are presented in the GEOSITE user's guide by Spigolon and Bakeer (in preparation) are intended for use in the preparation of future upgraded versions of the program.

The program diskettes accompanying the user's guide are read-only (i.e., any changes entered onto the display screens during a guidance session cannot be stored). The original development version of the program can only be modified by using the Microsoft FoxPro 2.5 Relational Database Management System. The original program diskettes reside with the Dredging Operations Technical Support Program (DOTS), USAE Waterways Experiment Station, ATTN: CEWES-EP-D, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199.

The rules developed for GEOSITE represent knowledge and expertise that were developed through professional experiences and research studies and therefore reflect the personal biases of the developers. It is most desirable that the present rules be critically reviewed by other geotechnical engineering and dredging experts and expanded or modified, as needed. The ideal knowledge base includes input from multiple experts who either reinforce each other or present valid alternate solutions to problems.

It is requested that users evaluate the program's usefulness, the screens, and the conclusions. The following represent a sampling of the many questions that could be asked by the developers. "With the conclusions that are stored in the Conclusions Memory after a query, are there any other conclusion displays that would be meaningful?" "Are there any other conclusions that should be drawn from the antecedents?" "Is the information contained in the Conclusions Display sufficiently complete that the user can understand and then utilize the guidance correctly?" "Are the program and the displays user-friendly?" "What else can or should be done to improve the usefulness of the GEOSITE program?" Proposed changes may be sent to the Manager of the DOTS Program at the Vicksburg address.

DREDGABL

The objective of DREDGABL is to provide guidance from geotechnical engineering and dredging experts for the interpretation of sediment test and observation data in terms of the dredgeability of the sediment. DREDGABL is intended for use by dredging project estimators and planners working for the Corps of Engineers, by dredging contractors, or by dredging consultants. It can also show to the geotechnical engineers and engineering geologists involved in dredging project site investigations what the important sediment properties are for dredgeability evaluation.

DREDGABL provides an expert evaluation of the dredgeability characteristics of specific sediments whose geotechnical properties are described in the dredging contract documents. Advice also is given about the suitability of various types of dredging equipment for use with those sediments, based on dredgeability characteristics. Expert knowledge is contained in several knowledge databases that are queried during operation of the program.

DREDGABL user's guide

The user's guide for DREDGABL, prepared by Spigolon and Bakeer (1994a), contains explicit detailed instructions for application of DREDGABL to a prototype dredging site and operational instruction for navigating through the DREDGABL program, in a manner similar to GEOSITE.

The DREDGABL user's guide contains instructions for installing and using DREDGABL for the geotechnical evaluation of the dredgeability of sediments.

The two diskettes for the Microsoft Windows version of DREDGABL are included with each copy of the user's guide. A limited number of the MS-DOS versions are available on request to the Scientific and Engineering Applications Center, Information Technology Laboratory, ATTN: CEWES-IM-DS, USAE Waterways Experiment Station, Vicksburg, MS 39180-6199.

Application of DREDGABL

Both the MS-DOS and the Windows versions of DREDGABL are user-friendly and support mouse input. Input is provided through a group of consultation screens, each containing a question with multiple-choice answers. Answers and/or screen controls are selected by mouse-pointer clicking or by the keyboard arrow keys and keystroke combinations. This eliminates the need for the user to type words or numbers for data input during guidance sessions. This is intended to accelerate the input process, eliminate typographical errors, and facilitate the use of the system by nontypists. The path through the input screens is not fixed; the question asked on each new screen is the result of the specific answer to the question posed on the previous screen.

DREDGABL starts with the assumption that available sediment geotechnical descriptor data are contained in the project plans specifications in the ASTM (1992) format, which is based on the USCS (HQUSACE 1960). The flow of the program through the group of display screens is shown in Figure 5.

The application of DREDGABL includes the following:

a. The first question requests the general type of sediment in the layer or deposit being evaluated. The general sediment type is defined as the predominant material found in the sediment being dredged or as the material corresponding to the median grain size, d_{50}.

b. If the sediment type is gravel or sand, DREDGABL requests the USCS/ASTM classification, sediment name, compactness, gradation fineness, and grain angularity.

c. If the sediment type is inorganic fines or organic fines, DREDGABL requests the USCS classification, sediment name, consistency, and PI. If the consistency is unknown, and the water content or the wetness is known, then it may be possible to estimate the consistency from the LL.

d. If the sediment type is in the "other sediments" category, then only the sediment name is required to identify the material. Properties of these materials may vary significantly, and there are no specific designations for them either in ASTM or USCS.

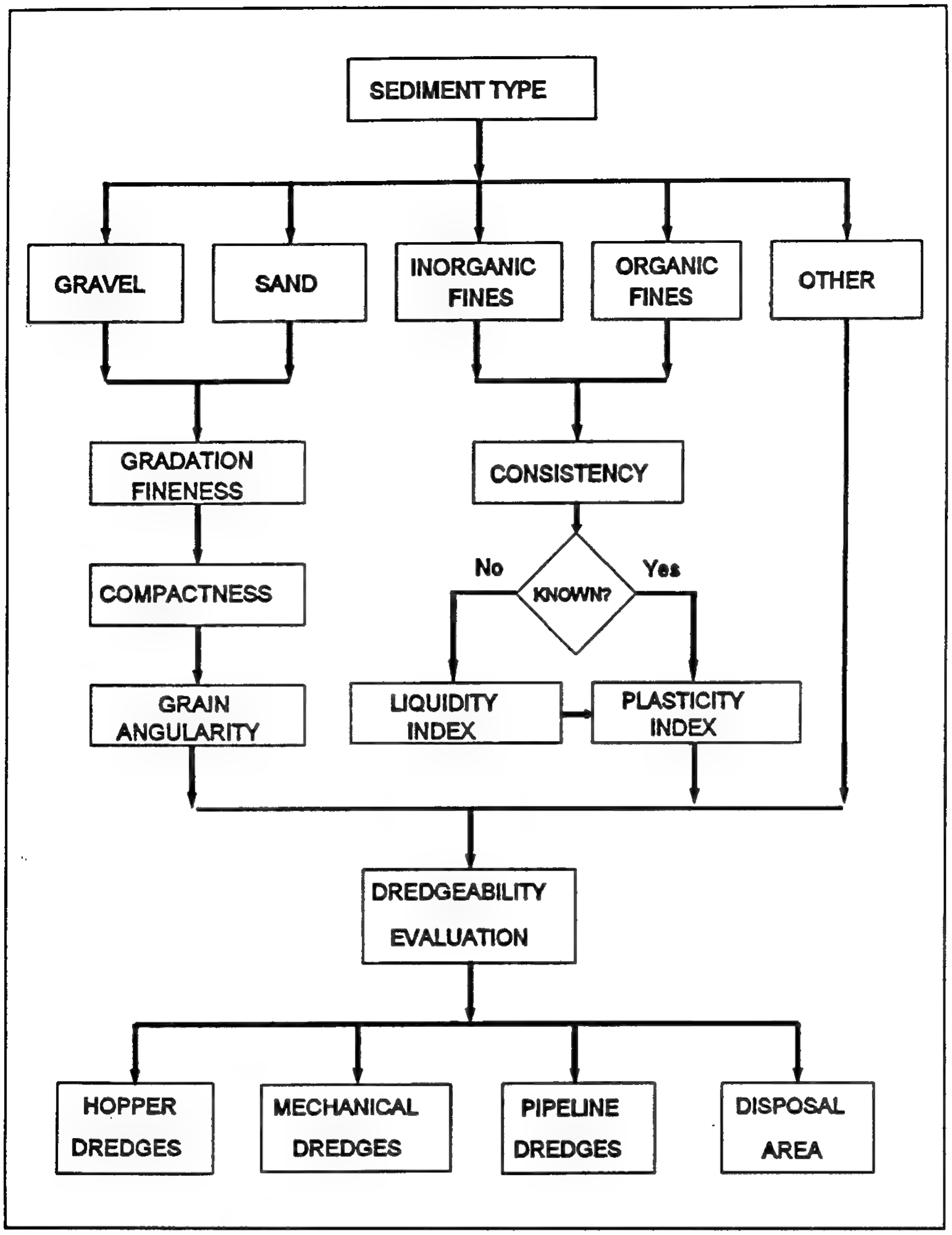

Figure 5. Flow diagram of DREDGABL screen displays (after Spigolon and Bakeer (1994a))

e. After all required antecedents are defined (including the possible choice of "unknown" in any category), DREDGABL evaluates this information and searches the appropriate knowledge base for conclusions about the dredgeability properties of the uniquely described sediment.

f. The user may then display DREDGABL's conclusions about the suitability of various generic types of hopper, mechanical, and pipeline dredges for use with the described sediment or may display the disposal

area properties. The user also may choose to print out the complete set of conclusions for the specific sediment.

g. Provision has been made in DREDGABL for the recording of information and knowledge about, and experiences with, local sediments that have been developed by the user's organization. This is locally derived information that amplifies or supersedes the information contained in the general knowledge bases. The LOCALINFO database may be viewed and the contents of any memorandum may be printed.

In the present version, DREDGABL considers only one sediment type at a time in its evaluation of the suitability of various dredge types for that sediment. Therefore, the user must run the DREDGABL program again for each layer or deposit in the dredging prism that has a unique set of properties.

DREDGABL problem-solving strategy

DREDGABL, as with GEOSITE, uses a forward-chaining or data-driven problem-solving strategy. The knowledge representation is rule-based, each rule consisting of a number of "IF<antecedents>...THEN<conclusion>" statements. One rule exists for each of the total finite number of options in the antecedents.

In the present version of DREDGABL, there are 1,035 unique sets of options. Ideally each unique set of antecedent options leads to a single conclusion. DREDGABL reaches 27 different conclusions for each unique set of antecedents, for a total of 27,945 possible conclusions. Inferencing can therefore be done as a standard database search, using the antecedents (IF statements) as search filters to find the conclusion records (THEN statements) that satisfy all of the unique query requirements. By using 27 conclusion fields for each record, the total number of records to be searched is reduced to the 1,035 possible sets of antecedents, greatly increasing the search speed of the system.

Modifying and upgrading DREDGABL

As with GEOSITE, the program details that are presented in the DREDGABL user's guide by Spigolon and Bakeer (1994a) are intended for use in the preparation of future upgraded versions of the program. Here, again, the program diskettes accompanying the user's guide are read-only. The original development version of the program can only be modified by using the Microsoft FoxPro 2.5 Relational Database Management system, which resides with the Manager of the DOTS Program at WES. The authors request that users evaluate the program's usefulness, screens, and conclusions by considering questions previously asked about GEOSITE. Critical comments and suggestions may be directed to the Manager of the DOTS Program.

The only database files that can be directly modified by the user in the distribution copies of the DREDGABL program is the LOCLINFO.DBF file. This file is modified by directly typing onto the memorandum display screen. Instructions for this task are included in the user's guide. A total of 16 records have been established in this version of DREDGABL, of which the first is used for the instructions. If more than 15 additional records are needed, a provision has been made for adding records. Record numbers and dates should be added to all additional records. There is no practical limit to the number and size of records that can be added except the limit of available space on the user's hard disk.

A local administrator may exercise input control by modifying the LOCLINFO.DBF database file attributes to make them read-only using a file management program such as Norton Commander or Norton Utilities, among others. Alternatively, similar programs may be used to require a password that can be supplied to the appropriate individuals.

5 Reducing the Impact of Contract Claims[1]

The objective of this study was to present knowledge and insight gained from geotechnical engineering research conducted by the Dredging Research Program (DRP) with results applicable for reducing the impact of contract claims at dredging projects. Dredging project contract claims can arise from various factors that cause the contractor to experience additional costs and/or time delays that result in lost profits and that are not under the contractor's control. These factors include site conditions, adverse weather, unusually rough sea conditions, change orders, and other unexpected time delays. Spigolon (in preparation) analyzed the contributions of DRP Technical Area 2 "Material Properties Related to Navigation and Dredging" to minimizing the impact of differing site condition claims.

Differing Site Conditions

There are risks inherent in any type of construction, including dredging. Risks to the owner (U.S. government) of a dredging project are due to site conditions (known or unknown, surface and subsurface) that may adversely affect the legitimate cost of having the specified work done by a contractor. Risks to the contractor include all the unforeseen surface and subsurface conditions that may adversely affect the contractor's production rate, costs, and legitimate profit. Each party to a proposed dredging project has decisions to make and commensurate risks to bear.

The owner decides where and when the dredging work is to be done and establishes the specifications for the conduct of the work. The contractor has no control over the owner's decision process. The owner also is responsible to the contractor for disclosing to the dredging contractor all available knowledge about subsurface conditions and other site conditions that may adversely affect the contractor's performance.

[1] Chapter 5 was extracted from Spigolon (in preparation).

FAR changed-conditions clause

The U.S. government, the major sponsor of dredging in the United States, has recognized that it, as the owner, has the responsibility to pay the dredging contractor's legitimate claims for the adverse effects of an unexpected change in site conditions. In all Corps of Engineers contracts for dredging, the Federal Acquisition Regulations (FAR) Differing Site Conditions/Changed Conditions clause, 48 C.F.R. 52.236-2, states:

> The Contractor shall promptly, and before the conditions are disturbed, give a written notice to the Contracting Officer of (1) subsurface or latent physical conditions at the site which differ materially from those indicated in this contract, or (2) unknown physical conditions at the site, of an unusual nature, which differ materially from those ordinarily encountered and generally recognized as inhering in work of the character provided for in the contract.
>
> The Contracting Officer shall investigate the site conditions promptly after receiving the notice. If the conditions do materially so differ and cause an increase or decrease in the Contractor's cost of, or the time required for, performing any part of the work under this contract, whether or not changed as a result of the conditions, an equitable adjustment shall be made under this clause and the contract modified in writing accordingly.

Factors leading to claims of differing site conditions

Justifiable claims for differing site conditions on dredging projects result from one or both of two factors when they are present on a project, with the underlying assumption that there is no attempt at fraud or misrepresentation by either the owner or the contractor:

a. Insufficient geotechnical site investigations.

b. Insufficient descriptions of site conditions.

Insufficient geotechnical site investigations. A major contributor to claims is the lack of sufficient subsurface information. Development of a dredging plan and cost estimate requires that both the contractor and government estimator be able to make a reasonable judgment about the location (horizontal and vertical) and the dredgeability characteristics of all sediment deposits in the dredging prism. Mobilization and employment of unsuitable or inefficient equipment not matched to the characteristics of the specific sediment can be very costly. In maintenance work there usually are acceptable historical records of productivity. In new work, however, the owner and contractor must substitute the subsurface investigation for historical knowledge.

There exist two different philosophical viewpoints about the desired magnitude of subsurface investigations by the owner prior to letting a dredging contract. One viewpoint is that the owner should investigate only just so far as needed for design purposes. This viewpoint holds that only a minimum of information should be created and given to the contractor because additional information could be misinterpreted and result in a claim. Furthermore, it is felt prospective contractors should have the right to make their own explorations and evaluations.

The second viewpoint feels that the owner has much more time for subsurface investigation than the prospective contractors. By providing all contractors with the same extensive and useful subsurface information, there is a so-called "level playing field" and the contractor assumes less risk. All contractors are then making bid estimates based on the same information and the owner assumes all of the risks due to unknown subsurface conditions. This is expected to inhibit the preparation of unreasonably low bids by inexperienced or uninformed contractors who would later submit costly claims that could have been avoided. This viewpoint believes that, over the long term, reducing contractor risk results in the lowest cost.

Insufficient descriptions of site conditions. Total and effective communication between the owner and prospective and actual contractors is essential for all concerned. Misunderstandings are a breeding ground for claims, whether based on fact or not. A major source of misunderstandings is insufficient and/or unclear descriptions of site conditions in contract documents, which is sometimes the result of a lack of consistent terminology. It is unfortunate that occasionally geotechnical engineers and dredging estimators for the contractor and the U.S. government do not speak exactly the same language.

Geotechnical engineers plan and execute subsurface investigations used for dredging projects, especially new work projects. New work projects are not routine events. It is understandable then that geotechnical engineers may not fully comprehend the need to define terms and describe sediments in a manner that both contractors and government estimators can understand. A glaring example of this results from the fact that soils are described almost exclusively in terms of the USCS. Knowledge of the median, or 50 percent, grain size is essential for sizing the pump and pipeline needed for the hydraulic transport of soils, particularly sands. The USCS classification groups for sand are far too broad with respect to the median size of grains to define this characteristic in a usable manner. Samples being laboratory tested will randomly fall into either the coarse-grained or fine-grained categories because of as little as a 1 percent change in the percentage of sample passing the No. 200 screen. As another example, knowledge of the in-situ strength of the soil or rock is necessary for evaluating its excavatability. Strength determination is not an essential part of the USCS.

DRP Contributions for Improved Site Information

The DRP has identified descriptors for sediments to be dredged (Spigolon 1993a), developed a geotechnical site-investigation strategy for dredging projects (Spigolon 1993b), and used a KBES for DREDGABL and GEOSITE to plan a subsurface investigation (Spigolon and Bakeer 1994a; in preparation), as discussed previously in this summary report. The DRP also produced several new products under other work units designed to reduce or eliminate adverse impacts of contractor claims arising from incomplete geotechnical information provided to potential dredging contractors. This new technology was developed to enhance the ability of the Corps of Engineers to obtain more precise and comprehensive geological data about proposed dredging projects, with particular reference to new work dredging, discussed by Spigolon (1993b).

Rapid geophysical technique for subbottom imaging

As part of the DRP, a system for acoustic impedance subbottom profiling was developed (McGee, Ballard, and Caulfield 1995). This is one of the relatively new geophysical survey methods that have the potential of being of great value in dredging subsurface investigations, particularly for providing preliminary continuous subsurface profile information. Because dredging is typically done on underwater sediments, acoustic subbottom profiling from a boat provides a rapid, economical, and effective geophysical method of obtaining general information about the site before any boring, test pit, or probing locations are planned.

This impedance technique for subbottom profiling uses a deliberately induced acoustic field in a modification of the seismic reflection technique commonly applied in offshore oil exploration, that has been tailored to shallow-water environments. In this method, sound energy is emitted from an acoustic source at or below the water surface. As the energy arrives at a boundary between two layers of different material properties, part of the energy will be reflected back toward the surface and part transmitted downward. The receiving system is also in the water, attached to a small boat.

Some of the transmitted energy will undergo absorption or attenuation in the layer while the remainder is transmitted to the next stratigraphic boundary. The time for a signal to be transmitted and reflected from a stratigraphic boundary, along with knowledge of the type of material (i.e., the sound wave velocity), is used to determine the thickness of the layer. Ratios between transmitted and reflected energy are dependent on the density and the sound wave velocity of the materials through which the energy is moving. Energy loss is a function of the frequency of the sound wave. Acoustic impedance is the product of transmission velocity (centimeters per second) and the density of the material (grams per cubic centimeter). By simultaneous use of two or more frequencies, both the stratigraphic boundary and the type of material can be estimated.

The acoustic impedance has been determined for a large number of sediment materials empirically. This was done because certain assumptions must be made about attenuation factors, and these require that site-specific borings be made for ground-truth data to calibrate the system.

The acoustic impedance system developed by the DRP consists of two commercially available instruments, a 3.5-kHz pinger system and an integrated, high definition 0.4- to 5.0-kHz boomer system. Reflected signals are picked up, amplified, filtered, and recorded with a specially designed digital data-acquisition system. By extension of the shipboard equipment to include global positioning system devices, the system can also detect the depth of the bottom and record it with a corresponding exact location. In this manner, a fully three-dimensional estimate of the sediment profile of the proposed dredging prism can be established.

Results from calibrated acoustic impedance surveys have been used to provide Corps Districts and dredging contractors with:

a. Density estimates of marine sediments. Estimates of in-situ density are derived from computed impedance values and corrected with ground truth information.

b. Continuous subbottom information for planning and designing dredging and sampling programs.

c. Estimates of the volume and type of material to be removed through dredging.

d. A detailed and continuous geologic database for aiding long-term planning of future work.

Inexpensive vibracoring sampling device

The shear strength of the sediments to be excavated must usually be determined from direct measurements. In the case of maintenance dredging where the strength of the newly shoaled material is relatively consistent from dredging cycle to dredging cycle, excavatability can be reasonably estimated from project records. In those cases, only a sample of the material without concurrent strength tests is sufficient for the laboratory measurement of the material (grain size) properties of the newly placed sediment. The same sample can be used for chemical tests if required. If the strength of the in-situ soil also is needed, as it would be in new work investigations, the vibrating tube sampler can be coupled with a cone penetrometer test or the dynamic solid cone test devices that do not obtain samples.

One of the most useful devices for obtaining samples of unconsolidated sands and fines is the vibrating tube corer. This type of device has been in use for over 30 years for obtaining continuous disturbed but representative

samples of cohesionless and fine-grained sediments on land and in shallow water. Such devices are relatively light in weight, are relatively inexpensive, and can be handled in a small boat by a crew of two or three.

There are several manufacturers of vibrating tube sampling devices worldwide. These devices create a disturbance whose magnitude depends on the effect of the vibration, the side friction in the tube, and the vertical stability of the tube during penetration. It would appear logical that the rate of penetration of a vibrating tube sampler be related to the compactness (relative density) of a cohesionless soil and/or the relative consistency of a cohesive soil.

Smith and Clausner (1993) described the development and use of an inexpensive shop-made vibrating tube sampling device. The cost of the power source, vibrator cable, and vibrator was less than $1,000 (1993 prices). The system uses 30-ft sections of aluminum irrigation pipe with 1.6-mm (1/16-in.) wall thickness. The pipe is cut to the desired length (i.e., the desired full length of the sample plus water depth plus about 0.6 m (2 ft) for the top of the tube to extend above water). A standard concrete vibrator is then attached to the top of the sampling tube and powered by a lightweight 5-hp, 4-cycle engine. In cohesionless soils, a sample retainer is used at the bottom end of the tube. The assembled tube and vibrator are hoisted with a boat-supported A-frame and lowered to the bottom. Vibration is started and the device enters the soil, securing a continuous sample. The hoist is used to retrieve the sample tube. A bilge pump is used to remove all excess water from the top of the sample. Both ends of the tube are sealed, and the sample is sent to the laboratory for material properties tests.

Drilling parameter recorder

It is more efficient to have a flexible subsurface investigation program under the direct field supervision of a geotechnical engineer so that the sampling and testing program can be modified as revelations of the subsurface investigation warrant, rather than an inflexible program based on a working hypothesis of site conditions. The drilling parameter recorder (DPR) permits the geotechnical engineer to make a rapid evaluation of rock parameters in the field as sampling and testing are proceeding (Smith 1994).

The DPR has been used in prototype investigations to characterize rock materials during subsurface exploration borings. This device provides a continuous record of parameters related to the characteristics of a rock layer with depth. In the DPR system, the following parameters are measured and recorded continuously:

a. Relative torque indicated by pressure to the hydraulic motor turning the drill string.

b. Downthrust on the drill bit.

c. Rate of advance (penetration speed).

d. Rotation rate.

e. Holdback pressure on the drill string.

f. Time to drill one digitized increment of depth. Benefits result from the exploration costs of drilled cored holes requiring casing versus less expensive roller bit holes (Smith 1994). For roller bit holes, it is not necessary to put down casings or take cores for most of the holes. A cored hole would be drilled near a roller bit hole where the DPR was used for correlation purposes. Then roller bit holes with the DPR would be drilled in the vicinity; if DPR characteristics remained constant, it would be concluded the materials are similar. Or, for the same amount of funding, a region of interest could be more intensely covered with roller bit borings. This is especially important in regions of variable site conditions.

Point load test for soft or saturated rock

Contractor's claims for differing site conditions when dredging rock are often based on changes of material strength. Strength characteristics of some rock, particularly soft sedimentary rock, depend on testing in in-situ moisture conditions. It is desirable during rock dredging projects, therefore, that a rapid on-site method be available for assessing the strength of rock, particularly rock pieces and broken cores.

The rock property commonly accepted for indicating strength, ripability, and dredgeability is the unconfined compressive strength (UCS). The UCS test requires considerable time, effort, and expense. The point load test (PLT) of rock is an index test that correlates well with the UCS for igneous and hard sedimentary rocks. Now the correlation is being extended to the softer saturated sedimentary rocks that are mechanically dredged in many coastal areas.

The PLT is a portable compression testing device typically having a capacity of 44.5 to 67 kN (10,000 to 15,000 lb) capable of testing high-strength rock. Pressure is normally applied by a hydraulic ram. The sample is compressed between two platens, each having 60-deg conical points with a 5-mm point radius. Cored samples may be tested diametrically or axially, with no further precise sizing of the sample dimensions required. Of greater importance is the fact that an irregular lump can be tested. It is suggested that several samples be tested from the same deposit and the results averaged (Smith 1994).

Although fairly reliable correlations exist between the PLT and UCS for igneous and hard sedimentary rock, the same is not true for soft saturated sedimentary rock. As a result, Smith (1994) assembled a database of test data for soft/saturated rock called the Point Load Index and Unconfined

Compressive Strength (PLUCS) database system. The PLUCS database contains results from over 400 rock tests from 10 different material sources.

Correlation of the point load index with UCS is material-type dependent, and such correlations are ideally based on a site study. The use of previously published hard-rock information to estimate UCS for weaker/saturated materials can easily yield results in error by a factor of two. PLUCS provides data for material-specific correlations based on tests performed on both dredged material and on other saturated rock materials selected for uniformity.

Advantages of the PLT, its application to dredging operations, and its application to soft saturated rock testing either during the initial subsurface investigation or for rapid assessment of rock strength in the field as a result of a claim, are:

a. The PLT is rapid; the testing machine is portable; and the test can be made in the field.

b. Sample preparation in the manner of the UCS is not necessary. A short core section or a lump of rock can be tested.

c. During the initial dredging exploration, samples can be tested in the in-situ saturated condition, improving the value of the strength test. The usual precautions for handling and storage of all the samples are eliminated.

d. The PLT is inexpensive relative to the UCS. The potential for cost savings exists because either (1) the total number of expensive laboratory UCS tests can be reduced, or (2) a larger total number of test measurements of rock strength can be made for the same cost, increasing the amount of information available from the exploration.

e. Claimed changes in material type can be tested immediately in the field, permitting on-site decisions about the validity of the claim. A costly and time-consuming claim evaluation process for both the owner and the contractor is more likely to be avoided by on-site evaluation of rock strength.

6 Synopsis

The research described in this summary report has developed geotechnical descriptors such that engineering properties of sediments to be dredged are either directly given or can be readily inferred for engineering applications such as dredgeability predictions. The term dredgeability is taken to mean the ability to excavate underwater, remove to the surface, transport, and deposit sediments with respect to known or assumed equipment, methods, and in-situ material characteristics.

Geotechnical Site-Investigation Strategy for Dredging Projects

The objective of a geotechnical site investigation for a dredging project is to obtain the most complete and accurate estimate of the location and character of the materials to be dredged that is possible within the limits of available time, money, and practicality. This information must be communicated in a readily understood manner to all persons involved in the design, cost estimation, and construction of the project. A site investigation for dredging consists of studies of all available existing information augmented by geophysical and geotechnical subbottom investigations, including the sampling and testing of soils. The data are summarized in an estimated geotechnical subbottom profile. The validity of the estimated profile is dependent on the type and amount of site investigation made and on the knowledge and skill of the interpreter(s) of the data.

Spigolon (1993b) has developed a strategy for a geotechnical site investigation for a dredging project. The procedure begins with a review of all existing information. Based on the prior information, an initial hypothesis of the geotechnical subbottom profile is developed, including the types, configuration, and geotechnical character of the subbottom soils present. If the available information is sufficient for the project, the site investigation is terminated. If not, then an estimate is made of site variability. If site variability is not well-known, then a geophysical survey may be appropriate. Where appropriate, continuous subbottom information is obtained by geophysical studies using acoustic subbottom profiling or other suitable methods. Ground-truth correlation is required. If the updated geotechnical information is now sufficient for

the project, the site investigation is terminated. If the amended subsurface profile estimate is still not sufficient, then a geotechnical physical site-exploration plan is formulated. The number and location of the test sites will be dictated by site variability. At each test site, specific depths and methods are selected for sampling and testing the subbottom materials. Sampling depth may be reached by drilling or digging pits. A description and classification is made for each sample. The new geotechnical information is summarized and reviewed for consistency with the previous profile estimate. If the revised subbottom profile estimate is now sufficient for the project, the site investigation is terminated. However, if more information is required, then additional geophysical and/or geotechnical sampling and testing are done. This iteration is continued until a point of sufficiency is reached.

If a dredging project is offered for bid with only minimal geotechnical knowledge available, then a cost associated with geotechnical risk will be part of the total project cost as reflected in the bid price. If a perfect geotechnical site investigation has been made, then the contractor has access to all knowledge needed to match equipment to soil type and character; to schedule equipment; and to determine fuel, personnel, and wear costs. There is absolutely no risk in the project due to lack of knowledge of the characteristics of the soils in the dredging prism. This savings in bid price is the value of perfect information and represents an upper limit of project savings due to the availability of complete geotechnical information.

Geotechnical Descriptors for Sediments to be Dredged

Soil properties data can be communicated in two basic ways: (a) using raw numerical soil identification test data, or (b) using descriptors. A descriptor is defined as "a word, phrase, or alphanumeric symbol used to identify an item." Numerical test data can be communicated easily using computer database methods. However, this method does not indicate or infer dredgeability directly. Descriptive terms provide word equivalents to the numbers resulting from soil identification tests. When numerical definitions for the words are consistent, word descriptors are practical for communicating information.

Descriptors for dredging-related soil properties can be (a) descriptive terms (words or phrases), (b) an arrangement of soil properties into classification groups with each group representing an assessment or rating of dredgeability, (c) test results from a specific test device or suite of devices, or (d) some combination of these. Spigolon (1993a), Leshchinsky (1994), and Richter and Leshchinsky (1994) have proposed consistent descriptive terms for sediments to be dredged. These descriptive terms are then related to a classification system for indicating or readily inferring the dredgeability of in-situ sediments.

The proposed dredging classification system places all materials in one of eight groups, each with different fundamental dredging characteristics. New work may encounter any of the eight groups. The eight groups are:

a. Rock and coral.

b. Shale and cemented soils.

c. Boulders and cobbles.

d. Clean granular soils.

e. Friable mixed-grain soils.

f. Cohesive soils.

g. Highly organic soils.

h. Fluid mud.

Each of these eight groups are considered from the standpoint of four different dredgeability property evaluations:

a. Geotechnical properties.

b. Excavation properties.

c. Removal and transport properties.

d. Disposal properties.

When the eight different kinds of materials are considered from four different dredgeability property evaluations, the dredgeability of the in-situ sediments can be directly indicated or readily inferred.

Geotechnical Evaluation of the Dredgeability of Sediments Using GEODREDG

Spigolon and Bakeer (1993) developed a KBES called GEODREDG to provide access to recorded expertise and guidance from experts in their respective fields for the use of:

a. Geotechnical engineers in the planning and execution of a subsurface investigation for a dredging project.

b. Dredging estimators and planners for interpreting geotechnical site-investigation data in terms of dredgeability.

GEODREDG consists of two interrelated KBES programs that have been developed as part of the overall system:

a. DREDGABL--guidance in the interpretation of geotechnical properties data for estimating the dredgeability of sediments. Intended to serve the planner or estimator as a personal geotechnical engineering and dredging expert consultant.

b. GEOSITE--guidance for geotechnical engineers and engineering geologists in the selection of methods and equipment for the sampling and strength testing, field and laboratory, of sediments to obtain the information necessary for evaluation of the dredgeability of the sediments.

GEOSITE

The objective of GEOSITE is to provide guidance from geotechnical engineering experts for the selection of equipment and methods for a subsurface investigation at an individual exploration site for a dredging project. It is assumed that the number and locations of the exploration sites have previously been established and that there is a general knowledge of the types of sediments to be expected at the site. The GEOSITE program recommends: (a) sediment sampling methods; (b) in-situ strength testing methods, considering appropriate sampler/testing method combinations; (c) methods for accessing the sampling/testing depth; (d) sediment field work platforms; and (e) material identification tests.

DREDGABL

The objective of DREDGABL is to provide guidance from geotechnical engineering and dredging experts for the interpretation of sediment test and observation data in terms of the dredgeability of the sediment. DREDGABL is intended for use by dredging project estimators and planners working for the owner (Corps of Engineers), dredging contractors, or dredging consultants. It can also show to the geotechnical engineers and engineering geologists involved in dredging project site investigations what the important sediment properties are for dredgeability evaluation.

DREDGABL provides an expert evaluation of the dredgeability characteristics of specific sediments whose geotechnical properties are described in the dredging contract documents. Advice also is given about the suitability of various types of dredging equipment for use with those sediments, based on dredgeability characteristics. Expert knowledge is contained in several knowledge databases that are queried during operation of the program.

DRP Contributions for Improved Site Information

The DRP has determined dredgeability and descriptors for sediments to be dredged (Spigolon 1993a), developed a geotechnical site-investigation strategy for dredging projects (Spigolon 1993b), and used a KBES for DREDGABL and GEOSITE to plan a subsurface investigation (Spigolon and Bakeer 1994a, in preparation). The DRP also produced several new products under other work units designed to reduce or eliminate adverse impacts of contractor claims arising from incomplete geotechnical information provided to potential dredging contractors. This new technology has been developed to enhance the ability of the Corps of Engineers to obtain more precise and comprehensive geophysical data about proposed dredging projects, with particular reference to new work dredging.

Rapid geophysical technique for subbottom imaging

A system for acoustic impedance subbottom profiling has been developed by McGee, Ballard, and Caulfield (1995). The impedance technique uses an induced acoustic field in a modification of the seismic reflection technique, but it has been tailored for use in shallow-water environments. By use of two or more frequencies simultaneously, both the stratigraphic boundary and the type of material can be estimated. By extension of the shipboard equipment to include global positioning system devices, the system can also detect the depth of the bottom and record it with a corresponding location. In this manner, a fully three-dimensional estimate of the sediment profile of the proposed dredging prism can be established.

Inexpensive vibracoring sampling device

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DPR

The DPR is aimed at permitting the geotechnical engineer to make a rapid evaluation of rock parameters in the field as sampling and testing are proceeding (Smith 1994). The DPR provides a continuous record of parameters related to the characteristics of a rock layer with depth. Benefits result from

the exploration costs of drilled cored holes requiring casing versus less expensive roller-bit holes. A cored hole would be drilled near a roller-bit hole where the DPR was used for correlation purposes. Then roller-bit holes with the DPR would be drilled in the vicinity, and if the DPR characteristics remain constant, it would be concluded that the materials are similar. Or, for the same amount of funding, a region of interest could be more intensely covered with roller-bit borings. This is especially important in regions of variable site conditions.

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References

Al-Hussaini, M. M. (1977). "Contributions to the engineering soil classification of cohesionless soils," Miscellaneous Paper S-77-21, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

American Society for Testing and Materials. (1992). "Natural building stones; Soil and rock; Geotextiles." *1992 Annual Book of ASTM Standards* 04-08, American Society for Testing and Materials, Philadelphia, PA.

Bartos, M. J. (1977). "Classification and engineering properties of dredged materials," Technical Report D-77-18, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Burmister, D. M. (1951). "Identification and classification of soils--An appraisal and statement of principles." *Proceedings, Symposium on the Identification and Classification of Soils, ASTM STP 113* 3-24, American Society for Testing and Materials, Philadelphia, PA.

Calhoun, C. C., Richardson, T. W., McNair, E. C., Jr., Engler, R. M., Smith, H. J., and Deloach, S. R. (1986). "Dredging Research Program development report," U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, and U.S. Army Engineer Topographic Laboratories, Fort Belvoir, VA.

Carrier, W. W., III. (1988). "Report on Session 2--Material Properties." *Hydraulic Fill Structures.* Geotechnical Special Publication No. 21, American Society of Civil Engineers, Ft. Collins, CO.

Casagrande, A. (1948). "Classification and identification of soils." *Transactions of the American Society of Civil Engineers* 113, 901-30, American Society of Civil Engineers, New York.

Demars, K. R., Chaney, R. C., and Richter, J. A. (1983). "The rapid carbonate analyzer," *Geotechnical Testing Journal* 6(1), 30, American Society for Testing and Materials, Philadelphia, PA.

Dumbleton, M. J. (1968). "The classification and description of soils for engineering purposes," Road Research Laboratory Report RRL 182, Ministry of Transportation, Crowthorne, England.

Eckert, J., and Callender, G. (1987). "Geotechnical engineering in the coastal zone," Instruction Report CERC-87-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Gibbs, H. J., and Holtz, W. G. (1957). "Research on determining the density of sands by spoon penetration testing." *Proceedings, 4th International Conference on Soil Mechanics and Foundation Engineering* 1, 35-9, London, England.

Herbich, John B. (1992). *Handbook of dredging engineering*. McGraw-Hill, Inc., New York.

Headquarters, U.S. Army Corps of Engineers. (1960). "The Unified Soil Classification System," Technical Memorandum No. 3-357, Department of the Army, Office of the Chief of Engineers, Washington, DC.

__________. (1970). "Laboratory soils testing," Engineer Manual 1110-2-1906, Department of the Army, Office of the Chief of Engineers, Washington, DC.

__________. (1987). "Confined disposal of dredged material," Engineer Manual 1110-2-5027, Department of the Army, Office of the Chief of Engineers, Washington, DC.

Landva, A. (1986). "In-situ testing of peat." *In-Situ '86: Use of in-situ tests in geotechnical engineering*. Special Publication No. 6, American Society of Civil Engineers, Blacksburg, VA.

Leshchinsky, D. (1994). "Descriptors for granular bottom sediments to be dredged," Contract Report DRP-94-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Marcuson, W. F., and Franklin, A. G. (1979). "State of the art of undisturbed sampling of cohesionless soils," Miscellaneous Paper GL-79-16, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

McGee, Richard G., Ballard, Robert F., Jr., and Caulfield, David D. (1995). "A technique to assess the characteristics of bottom and subbottom marine sediments," Technical Report DRP-95-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Permanent International Association of Navigation Congresses. (1984). "Classification of soils and rocks to be dredged," Report of a Working Group of the Permanent Technical Committee II, Supplement to Bulletin No. 47, Permanent International Association of Navigation Congresses, Brussels, Belgium.

Richter, S. D., and Leshchinsky, D. (1994). "Hydraulically transported clay balls," Contract Report DRP-94-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Skempton, A. W. (1986). "Standard penetration test procedures and the effects in sands of overburden pressure, relative density, particle size, ageing, and overconsolidation," *Geotechnique* 36 (3), 425-47.

Smith, H. J. (1994). "Improving site characterization for rock dredging using a drilling parameter recorder and the point load test," Technical Report DRP-94-5, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Smith, J. B., and Clausner, J. E. (1993). "An inexpensive method for vibracoring sands and fine-grained sediments in shallow water," Dredging Research Technical Notes DRP-2-06, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Sowers, G. F. (1979). *Soil mechanics and foundations: Geotechnical engineering*. 4th edition, MacMillan Publishing Co., New York, 20-31.

Spigolon, S. J. (1993a). "Geotechnical factors in the dredgeability of sediments; Report 1, Geotechnical descriptors for sediments to be dredged," Contract Report DRP-93-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

__________. (1993b). "Geotechnical factors in the dredgeability of sediments, Report 2, Geotechnical site investigation strategy for dredging projects," Contract Report DRP-93-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

__________. "Geotechnical factors in the dredgeability of sediments, Report 4, Reducing the impact of contract claims," in preparation, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Spigolon, S. J., and Bakeer, R. M. (1993). "Geotechnical factors in the dredgeability of sediments, Report 3, Guidance in the geotechnical evaluation of the dredgeability of sediments using GEODREDG," Contract Report DRP-93-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

__________. (1994a). "DREDGABL: Geotechnical factors in DREDGeABiLity, user's guide," Instruction Report DRP-94-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Spigolon, S. J., and Bakeer, R. M. (1994b). "GEOtechnical SITE-investigation methods (GEOSITE)," Dredging Research Technical Notes DRP-2-10, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

_________. (1994c). "Geotechnical factors in DREDGeABiLity (DREDGABL)," Dredging Research Technical Notes DRP-2-11, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

_________. "GEOSITE: GEOtechnical SITE-investigation methods, user's guide," in preparation, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Wentworth, C. K. (1922). "A scale of grade and class terms for clastic sediments," *Journal of Geology* 30, 377-92.

Appendix A
Sediment Sampling[1]

Three terms regarding soil sampling deserve strict definition: in-situ, undisturbed sample, and representative sample. In-situ derives from the Latin expression translated as "at the site" and is generally used to indicate the condition of a soil as it exists in its naturally placed location before intervention by man or machine. A truly undisturbed sample is one that maintains all of the in-situ soil mass characteristics (including shape, volume, pore pressure and size, and grain orientation and structure) and the in-situ horizontal and vertical pressures. In reality, a so-called undisturbed sample cannot completely retain all of these attributes. A representative sample may be remolded slightly or completely; i.e., it contains all of the soil materials, both solids and fluids, of its in-situ state but does not maintain the structure, grain orientation, or in-situ density. Such samples are appropriate for soil material property tests but not for soil mass properties tests. Laboratory strength tests of clays are heavily dependent on undisturbed sampling.

Sediment Samplers

Thin-wall tube sampler

Undisturbed tube sampling requires careful sampling technique. Sampling must be done from a stable platform; the tube must be inserted with a slow steady push without impact or vibration, requires considerable time and effort for sealing the sample tubes, and care must be taken in sample extrusion and handling. Vibration or shock during transport can totally destroy the structure of loose silt samples. Marcuson and Franklin (1979) have discussed the near impossibility of undisturbed tube sampling of sands.

[1] Appendix A was extracted from Spigolon and Bakeer (1993b). References cited in this appendix are listed following the main text.

Diamond core barrel sampler

Extremely hard soils such as shale, cemented soils, and rock are too hard for sampling by the direct insertion of a metal tube. Therefore, an undisturbed core is obtained by fitting the circular end of the sampling tube with a hardened steel cutting surface or bit. For cutting rock, industrial diamonds are imbedded in the cutting edge. Hydraulic pressure and rotation cause abrasion of the material from the annular space between the core and the wall of the drill hole. Water or drilling fluid is circulated down the drill stem between the core and the inner face of the single-tube core barrel. The core is retained in the barrel and retrieved. When the rock is erodible because of softness due to decomposition or interlaminated soil materials, a double tube core barrel must be used.

Split-tube sampler

Impact or percussion is used to drive a thick-wall split-tube sampler. This device is capable of penetrating and retaining a wide variety of soil types and consistencies and is usually deployed in a small-diameter drilled hole. Although extremely useful as a sampling device, this type of sampler requires a stable drive platform, a heavy drop weight, and somewhat longer time to operate than other sampler types.

Gravity-projectile tube sampler

Various types of tube samplers are available that are intended to penetrate the surface of an underwater soil deposit using dynamic force (gravity) as a projectile. Gravity-projectile corers use a heavy weight attached to the tube to provide the penetration force. Projectile samplers are remotely operated and do not require a stable platform. They may be advantageously operated from floating platforms, boats, or barges of modest size.

Vibrating-tube sampler

High-frequency vibration of the sampler during pushing is another means of inserting a sample tube into a soil deposit. There are several manufacturers of vibracorer devices worldwide. As a typical example of vibrating-tube coring devices, one proprietary device uses high-frequency (7,000 to 12,000 vibrations per minute) and low-amplitude vibration applied to the drill string to shear the soils in the immediate vicinity of the cutting edge of the core barrel. This permits the device to enter unconsolidated granular and cohesive deposits at rates up to 1.5 m (5 ft) per minute.

Bucket-auger sampler

A bucket auger consists of a fairly short metal tube, open at top and connected to a drill rod. The partially closed bottom is provided with an open cutting edge for drilling and for retaining the excavated, highly disturbed sediment sample. Various cutting edges are available for drilling in different types of sediments. Bucket sizes range from 2 to 3 in. to over 24 in. in diameter. A small-diameter bucket auger may be operated by hand; larger diameter buckets require machine rotation and handling in and out of the bore hole.

Surface-grab sampler

Various designs of grabs, scoops, buckets, and push tubes have been successfully used for offshore recovery of representative samples of granular materials from the surface of the bottom. The samples are invariably disturbed so that little semblance of the original structure remains.

Liquid-slurry sampler

Undisturbed sampling of a fluid mud is virtually impossible because the material has an extremely low shear strength and therefore behaves as a fluid; i.e., it will alter its shape to assume the shape of its container. However, representative sampling of a fluid mud is possible.

Working Platforms for Underwater Sampling

The drilling, penetrating, sampling, and in-situ testing of soil sediments under water requires a stable platform for (a) attaching the penetrometer or casing, drill stem, and auger from the underwater soil surface to the machinery on the platform; (b) holding personnel, machinery, and equipment; and (c) providing working space.

Bottom-supported, movable platforms

Either fixed length or extendable legs (spuds) may be used to support a drilling platform on the bottom. This type of platform permits work above the level of waves and tides. Fixed drill casing may be used and the necessary stability is provided for all types of sampling and in-situ testing equipment. The bottom-supported platform may be floating or nonfloating. The floating type may be towed from one site to another after retraction of the support legs from the bottom. Sampling and testing operations may include undisturbed soil sampling, standard penetration testing, vane shear testing, vibracorer sampling, and shallow seismic reflection profiling.

Floating platforms

Floating site investigation platforms are either (a) self-propelled ships or small boats, or (b) towed barges or pontoons. Self-propelled units have a higher capital cost and crew demands but have the advantage of being self-contained and mobile. All floating platforms are affected by the wind, waves, and tides, making attachment to a fixed drill-casing system nearly impossible. The tide and wave action are accounted for by anchoring, the use of spud bars, and special onboard heave compensators. Floating platforms are ideal for use with vibrating-tube samplers, bottom-supported devices, or diver-operated sampling devices because the connections to the platform are flexible.

Submersible bottom-supported, surface-operated machines

Submersible tethered systems, either fixed or movable, rest on the bottom and can be operated from a surface vessel using flexible connections. The devices permit drilling, sampling, field soil testing, acoustic measurements, vane-shear and cone penetration determinations, and undisturbed tube sampling. Units of this type tend to be very expensive and require highly skilled operators.

Diver-operated systems

The U.S. Navy has developed a suite of diver-operated sampling and testing devices, including an impact sample tube, a miniature standard penetration tester, a vane shear tester, a rock classifier (basically a Schmidt Hammer), a jetted depth probe, and a vacuum-assisted sampler. These devices have the inherent advantage of ease of movement with direct rather than remote control of the submersible devices.

Appendix B
Sediment Test Methods[1]

Geotechnical Tests

Soil material property tests

Most of the geotechnical soil test methods of particular relevance to dredging operations have been standardized by nationally recognized organizations such as the American Society for Testing and Materials (ASTM) (1992), and by the U.S. Army Corps of Engineers (USACE) (Headquarters (HQ) USACE 1970). The geotechnical soil material properties are those of disturbed and completely remolded material.

Use of saltwater in laboratory soil tests. HQUSACE (1987) recommends the use of saltwater at the in-situ salinity for "...all (sediment) characterization tests and in the settling tests." The sediment characterization tests include the sedimentation part of grain-size analysis (hydrometer test), Atterberg limits, and specific gravity of grains. Eckert and Callender (1987) also recommend adding water at the in-situ salinity to all tests requiring addition of water.

Particle-size distribution. The fractionation of a soil into size groups is generally done by mechanical screening on a nest of sieves of different sized screen openings. The use of screens to fractionate silt- and clay-sized particles smaller than about 0.075 mm (No. 200 screen) is impractical because of the fineness of the screens and their tendency to become clogged with particles. A laboratory test using a hydrometer has previously been utilized to measure slurry density instead of using screens for fine-grained materials. Recently, the tedious methodology of the hydrometer test has been supplanted by electro-resistance multichannel particle-size analyzers such as the Coulter Counter. If only the amount of clay sizes is needed rather than the distribution, then two cost-effective alternative methods, the decantation method and the pipette method, should be considered.

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[1] Appendix B was extracted from Spigolon (1993b). References cited in this appendix are listed following the main text.

Analysis of grain-size data. The gradation information of interest concerns maximum size (d_{max}), median grain size (d_{50}), some measure of uniformity (such as d_{60}/d_{10}), dispersion (d_{85}, d_{15}), and fines content (-No. 200 screen size). The use of a plotted curve permits visual determination of the grain size corresponding to any percentage finer or coarser, especially if the percentage is not coincident with a standard sieve size.

Sedimentation rate in saline water. The settling rate of the clay fraction must be determined using water of the same salinity as will be encountered in-situ. The test method for flocculated settlement is given by HQUSACE (1987).

Atterberg limits. The Atterberg tests of liquid limit (LL) and plasticity index (PI) are performed on all material in a soil finer than 0.425 mm (No. 40 screen). The LL and PI are high for a montmorillonite clay, intermediate for illite, and low for kaolinite.

Liquid limit:

> A pat of wet soil is placed in a shallow flat cup and a standard size groove is cut in the soil. The cup is impacted by free falling onto a standard base, and the number of impacts to cause the groove to close a distance of 1/2 in. is counted; a sample of this soil is tested for water content. The soil is slightly wetted or dried as needed and another test made. This is continued until several points requiring more and less than 25 blows is completed. A semilog plot of water content versus number of blows is made and a regression line drawn through the points. The water content corresponding to 25 blows is the LL water content.

Plastic index:

> A moist soil is rolled by hand until it forms a thread 3 mm (1/8 in.) in diameter. This is continued by slightly drying the soil for succeeding trials until the water content is reached at which the threads will begin to crumble on reaching the 3-mm (1/8-in.) diameter. The soil is then at the plastic limit water content.

Correlation of Atterberg limits and clay content. Every clay soil type appears to have a unique correlation between its LL and its PI with percent clay. Given the correlation for a specific locality, the clay content as a percent of the -No. 40 screen fraction can be used to estimate the LL and/or the PI.

Grain angularity and shape. Grain angularity and shape are most easily determined by visual comparison with standards. The simplest of these systems is the visual-manual procedure where pictures of rounded, subrounded, subangular, and angular grains are used for comparison. Particle shape is easily identified as flat, elongated, or flat and elongated particles.

Grain hardness. Grain hardness can only be defined in terms of the test procedure used to identify it. The most commonly used hardness test for rock and for rock fragments (soil) is Mohs' relative hardness scale. As a simple field test, the hardness of gravel particles may be tested by striking the grains with a hammer.

Organic content. Bartos (1977) proposed a dry combustion procedure for determining organic content of dredged materials that involved (a) drying a sample to constant weight at 110 °C, and (b) after weighing the dried sample, burning off the organics at 440 °C in a furnace for 4 hr. The ash content is the uncombusted residue, mostly clay minerals. ASTM (1992) defines peat as having less than 25 percent ash.

Carbonate content. Demars, Chaney, and Richter (1983) discussed several methods for determination of both the presence and the amount of carbonate mineral in soil and rock. The presence but not the amount of carbonates may be expediently tested by using dilute hydrochloric acid. A drop or two on a soil sample will cause a reaction in the presence of carbonates.

Specific gravity of grains. The specific gravity of soil grains is usually determined by laboratory testing. A dried sample is weighed in air. The same sample is immersed in water and the loss in weight (displacement) is used to determine the volume.

Salinity of pore water. HQUSACE (1987) discusses two ways to determine the salinity of pore water: determination of electrical conductivity and measurement of dissolved solids or nonfilterable residue. A conductivity meter electronically converts conductivity adjusted for temperature into salinity. The dissolved solids procedure involves filtration of water from the soil, evaporation of the water, and weighing of the solid residue.

Visual-manual soil tests. These methods are intended to be performed in a field situation without the need for laboratory equipment. Grain angularity and shape are easily determined by this test. Color is useful in stratum correlation. Odor is an immediate indicator of organics or chemical pollutants. The dry strength of a clayey soil is an indicator of plasticity index. The dilatency test indicates the absence or presence of clay particles in a fine-grained soil.

Soil mass property tests

Many of the engineering behavior properties of a soil mass are directly related to the bulk density and the water content.

Density. The density (unit weight) of a soil deposit is measured as weight per unit of volume. With water content known, the dry solids density can be calculated. With the addition of specific gravity of grains, the solids volume and gas content can be determined. All these parameters are useful in dredging production calculations.

Relatively undisturbed samples may be taken from soft to stiff cohesive soils by using a thin-walled sampling tube inserted into the soil slowly and without impact. Granular soils are almost impossible to sample undisturbed in a test boring or pit.

Nuclear in-situ bulk density devices determine soil density by measuring the attenuation of gamma radiation in a specific time period and comparing to correlation standards. Some of these devices may be used to determine both density and water content.

Acoustic methods for in-situ density determination involve the direct transmission of sound waves through the soil or slurry. The echo sounding technique achieves penetration into layers of increasing density by varying the wave frequency.

Water content. The natural water content of a soil must be accurately known for calculation of dry density and degree of saturation. The standard drying test for water content is based on measuring the loss of water from drying a soil specimen at a constant drying temperature of 110 °C. Equipment is available for measuring in-situ water content using a nuclear moisture gauge, usually in conjunction with nuclear field density testing. A patented chemical moisture method combines calcium carbide with water to form acetylene gas. The gas pressure formed in a closed container is directly related to water content expressed as a percent of total weight.

Soil behavior property tests

Probably the most fundamentally basic engineering behavior property of a soil is the material shear strength.

Direct shear strength. Because of the difficulty of obtaining an undisturbed sample, direct tests of shear strength are usually limited to cohesive soils. Application of the test results requires a theoretical model base that is only partially developed for dredging excavation operations. Direct shear strength tests are as follows:

a. Field vane shear test. The field vane shear test measures the shear strength of a cohesive soil in a manner resembling an unconsolidated-undrained direct shear test, only vertically. The soil must be soft enough so that the thin blades will not deform during the test. The shear strength measured by the vane shear tester is one-half of the unconfined compressive strength (Spigolon 1993b).

b. *Laboratory vane shear test.* A miniature shear vane having dimensions scaled down relative to those of the field vane shear test is used to provide a rapid test of an undisturbed clay soil specimen. This is most often done on a thin-wall tube sample of a clayey sediment. Several tests can be made along a short length of sample to determine variations of strength with depth.

c. *Unconfined compression test.* Under the large strain rates used in dredging operations, soils shear in an undrained manner. The simplest and most straightforward undrained shear strength test of cohesive soils is the unconfined compressive strength test. This unconsolidated-undrained triaxial compression test simulates the shear strength available under rapid undrained shear. A cylindrical undisturbed sample with height twice the diameter is tested in simple compression, without confining pressure, to failure within 1 to 2 min. Water content and bulk density of the sample are normally measured in conjunction with the test. The unconfined compressive strength of clays and shales tested at very rapid strain rates such as those occurring during very rapid cutting increases by 30-40 percent or more over the strength from the common laboratory test made at a slower rate.

d. *Compression test of thick-wall tube cohesive sample.* The unconfined compression test of a thick-wall tube sample can give a useful relative consistency if the cohesive soil is not very sensitive to remolding. For a sensitive soil, this test is not as accurate as a compression test made on a thin-wall tube sample, since the effect of remolding is to cause a decrease in strength.

e. *Hand-held strength testing devices.* Hand-held mechanical devices are used to estimate the unconfined compressive strength of clays. These methods provide only a rough estimate of consistency; however, this may be sufficient for checking the validity of the primary test.

Indirect shear strength. Commonly used indirect tests for estimating shear strength include various types of penetration tests, either dynamic or static. The Standard Penetration Test (SPT) is a dynamic impact test, and the Cone Penetration Test (CPT) is a quasi-static test. The various in-situ penetration tests have considerable value and merit in dredging-related site investigations. Because they reflect the shear strength of the soil, they also indirectly indicate the difficulty of cutting or eroding the soil. Indirect shear strength tests are as follows:

a. *SPT.* A thick-walled split barrel sampler is attached to the end of a drill rod string and placed at the cleaned-out bottom of a drill hole. A 63.5-kg (140-lb) drop hammer is placed over the top of the drill string. The hammer is raised and allowed to drop freely a distance of 76 cm (30 in.) onto the top of the drill rod, forcing the sampler into the soil. The sampler is first driven 15 cm (6 in.), and the number of blows to drive the sampler another 30 cm (12 in.) is recorded as the STP blow

count. The STP blow count is correlated with the relative density of the material, although validated adjustments must be made because of the effect of (1) different hammer designs, (2) different drill rod sizes, and (3) different methods of operation.

b. *Dynamic penetrometer test (DPT).* Virtually all soil probing or sounding is done to evaluate or estimate the relative in-situ strength of a soil. Where successive layers vary widely in strength or hardness, the driving of a metal probing device can be used to define relative strength and stratum changes with fair to good accuracy. A cone-tipped penetrometer rod or similar device can be continuously impact-driven using a machine- or hand-operated drop weight. Continuous driving obviates the need to withdraw the rods after each test. This method may be useful and cost-effective in investigating maintenance dredging areas. Accurate measurement of in-situ strength will require correlation of sounding rod penetration resistance with another standard method.

c. *Underwater CPT.* Various devices have been developed for performing cone penetrometer tests at sea, using a reaction frame resting on the sea bottom. One of the most interesting of these devices can be used to make continuous electric cone penetrometer profiles and can take push tube samples of the soil. Unless it is anchored to the bottom, the weight of the total device must be sufficient to provide all of the needed force reaction.

Selection of type of shear strength test. All static and dynamic in-situ shear strength test methods have distinct advantages and disadvantages, all of which should be thoroughly investigated to determine the most appropriate test for the specific situation. The objective of the in-situ test is to indicate the suitability of equipment and the energy needed to erode, cut, or scoop a given soil. How that decision is reached is somewhat immaterial; it requires only that (a) the decision be reached with maximum confidence consistent with least cost, and (b) the decision be implemented in a way that rigorously complies with a well-known published standard so there is no confusion as to what is being measured, and what it may be appropriately correlated to.

Geophysical Methods

Using direct contact with the soil deposit at various points, a large mass of soil can be investigated using electrical, acoustical, or seismic waves transmitted through the mass. Geophysical methods are indirect and non-intrusive and are generally characterized by large-scale measurements that produce an averaging of the soil properties over the zone of test influence. These do not include the capability of obtaining or testing a specific sample.

The distinguishing character of all geophysical methods is the ability to provide a continuous soil profile with only a few general soil characteristics

indicated. These methods require extensive calibration, usually with ground-truth studies of the in-situ project soils. Ground-truth tests indicate only the characteristics of the soils in the immediate vicinity of the boring or pit. Extrapolation of the data between borings or pits requires considerable interpretation of all other available data. Stratification that may be inferred from one boring or a group of borings may not be valid because of discontinuities or inclusions that have been missed. Drilling and profiling are complementary in many ways. The strength of one is the weakness of the other, and vice versa.

Most available geophysical systems can be operated from a vessel, many while the vessel is moving.

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Standard dredging-related geotechnical descriptors are needed so that engineering properties can either be given directly or be readily inferred for engineering applications such as dredgeability. Descriptive terms were developed that are related to a classification system for inferring the dredgeability of in-situ sediments. Also, a knowledge-based expert system (KBES) was developed to provide access to recorded expertise and guidance from experts in their respective fields for use by geotechnical engineers planning a subsurface investigation and by dredging estimators and contractors for interpreting the dredgeability of a proposed dredging project. The KBES GEODREDGE consists of two modules: (a) DREDGABL provides guidance in interpretation of geotechnical properties data for estimating the dredgeability of sediments; (b) GEOSITE contains guidance in the selection of methods and equipment for determining dredgeability. Several Dredging Research Program (DRP) products were identified that were designed to reduce or eliminate adverse impacts of contractor claims of changed conditions arising from incomplete geotechnical information provided to potential dredging contractors. The proposed dredging classification system places all subbottom materials in one of eight groups, each with differing fundamental dredging characteristics.

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